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Title: Methods, models, tools to assess the hydromorphology of rivers - Part 2
Thematic Annexes on monitoring indicators and models

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Summary

Background and Introduction to Deliverable 6.2

Work Package 6 of REFORM focuses on monitoring protocols, survey methods, assessment procedures, guidelines and other tools for characterising the consequences of physical degradation and restoration, and for planning and designing successful river restoration and mitigation measures and programmes.

Deliverable 6.2 of Work Package 6 is the final report on methods, models and tools to assess the hydromorphology of rivers. This report summarises the outputs of Tasks 6.1 (Selection of indicators for cost-effective monitoring and development of monitoring protocols to assess river degradation and restoration), 6.2 (Improve existing methods to survey and assess the hydromorphology of river ecosystems), and 6.3 (Identification and selection of existing hydromorphological and ecological models and tools suitable to plan and evaluate river restoration).

The deliverable is structured in five parts. Part 1 provides an overall framework for hydromorphological assessment. Part 2 (this volume) includes thematic annexes on protocols for monitoring indicators and models. Part 3 is a detailed guidebook for the application of the Morphological Quality Index (MQI). Part 4 describes the Geomorphic Units survey and classification System. Part 5 includes a series of applications to some case studies of some of the tools and methods reported in the previous parts.

Summary of Deliverable 6.2 Part 2

Part 2 of Deliverable 6.2 provides detailed information on some specific aspect outlined in Part 1.

In Annex A, a series of indicators is presented for the different stages of hydrological characterization, assessment of current status (alteration) and design (rehabilitation measures), including groundwater – surface water indicators.

Annex B reviews monitoring indicators, evaluation tools, and analyses which are suitable for monitoring morphological conditions.

Annex C reports monitoring protocols for riparian vegetation.

In Annex D, a summary of models used in hydromorphology is reported.

Acknowledgements

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ANNEX A Hydrological monitoring indicators

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ISPRA, Italy

Summary
In this document, a series of indicators is presented for the different stages of hydrological characterization, assessment of current status (alteration) and design (rehabilitation measures), starting from those already presented in REFORM Deliverable 2.1. Moreover, methods and indicators of groundwater - surface water interaction, highlighting the crucial role of GW-SW interaction in the hydrological response of the river system as a whole, are suggested.

The spatial scale we focus on is the river segment or reach, where we consider a certain discharge as uniform. The data needed for the assessment range from daily to hourly discharge time series and, for the purposes of design, groundwater levels or spring discharges.

For each group of indicators, the appropriate reference spatial scale and type of data is reported.

Glossary
*Baseflow*: The portion of stream discharge attributable to groundwater flowing from the "point source" or "linear springs" into the stream network; "baseflow is not attributable to direct runoff from precipitation or melting snow" (USGS, Glossary of Hydrologic terms).
*Baseflow index*: Ratio between baseflow and total discharge from a river section in a given time interval.
*Catchment (or watershed) area*: Drainage area, bounded by the line of the watershed, from which surface runoff is collected into the hydrographic network (also: Area of land draining into a stream at a given location, Chow et al., 1988).
*Effective infiltration*: Portion of infiltrated water that reaches the water table (saturated zone), and corresponds to the actual groundwater recharge (Kresic and Stevanovic, 2010).
*Flow regime*: Set of quantitative and temporal features of annual streamflow.
*Groundwater flow*: Water from effective infiltration which feed springs and streams through subsurface pathways.
*Hydrological cycle*: Cycle of water flow into (precipitation), through (surface, soil and groundwater pathways) and from (streamflow) a catchment.
*Infiltration*: Water movement through the land surface into the subsurface (Kresic and Stevanovic, 2010).
*Intermittent stream*: Stream which does not support continuous surface flow.
*Mean annual hydrological cycle*: Typical (long-term) cycle of water flow into, through and from a catchment over at least a 20 year period.
*Perennial stream*: Stream that supports perennial flow; during dry periods, perennial streams are fed by groundwater.
*Recharge area*: Area in which water reaches the zone of saturation by surface infiltration (Heath, 1984).
*Recharge of the aquifer*: The process of addition of water to the saturated zone.
*Surface Runoff*: the portion of rainfall that flows over the land surface to the drainage network during rainfall events.
*Temporary stream*: stream that contains water only occasionally, for example, only during rainfall or snow melt.
*Water budget*: quantitative assessment of water volumes coming into and leaving a catchment or other water body (e.g. aquifer, lake) over a particular time period.
*Water Resources*: renewable water volumes yielded by gravity from hydrogeological units (Castany, 1982). Usable water resources are only a portion of the total water resource, because they must allow for the water required to maintain the flow of perennial streams and the good status of surface ecosystems.
A.1 Indicators of hydrologic characterization

Spatial scale: Segment/reach
Type of data: Daily river discharge series

Hydrological characterization of a stream is based on the analysis of indicators of the response of the river basin to climatic (precipitation, air temperature), hydrogeological, geomorphological and land cover conditions.

The methodology for hydrological characterization is reported in D2.1, Part 2 Annex C – “Flow regime analysis and Hydrological Alteration”, and in the D6.2 Main Report.

The relevant hydrological indicators are listed in Table A.1.

Table A.1 List of hydrological indicators.

| Hydrological Indicators and assessed parameters (Poff, 1996) | Assessment methods |
|------------------------------------------------------------|--|------------------|
| QMean (Daily mean discharge, m³/s)                           | Time series of hydrological records (mean daily discharge recorded at a gauging station located at the outlet of the river segment or reach; at least 20 years of records are needed) usually derived from water level values recorded at gauging stations that are transformed into discharges using discharge/runoff - stage calibration curves. |
| DAYCV – Daily discharge coefficient of variation, %         | Starting from the listed characterization indicators (left column), a flow regime classification is applied, which determines the type of flow regime supported by the river segment or reach. |
| Average (across all years) of ((the standard deviation of daily discharge within the year divided by the annual mean discharge) x 100). | |
| FLDREQ – Flood frequency, 1/yr                              | The Flow regime classification method allocates streams to one of nine types based on the flow regime's: (1) intermittency/perennity; (2) groundwater-surface water interaction; (3) type of prevailing water sources that is feeding the river flows: (rainfall, snow and ice melt, groundwater seepage). |
| The average number of floods per year having a discharge higher than the mean of the annual maximum daily discharge (fixed flood threshold). | |
| FLDPRED – Seasonal flood predictability                     | |
| The maximum proportion of all floods over the fixed flood threshold that fall into one of six “60-day seasonal windows”, divided by the total number of floods. It ranges from 0.167 (absence of seasonality) to 1 (complete predictability of floods). | |
| FLDTIME – Timing of floods; day                             | |
| The day number of the first day of the 60-day period when FLDPRED is highest. The first 60-day period is January-February and it includes February 29. | |
| BFI – Base Flow index, %                                    | |
| Annual mean of the monthly ratios of the “minimum of monthly discharge” to the “mean monthly discharge”, multiplied by 100 | |
| ZERODAY – Extent of intermittency (number of days)          | |
| The average number of days in a year having zero discharge | |

The flow regime characterization identifies nine types of rivers on the basis of their flow:
- Intermittency;
- Groundwater contribution (e.g. baseflow);
- Prevailing water source (rainfall, snowmelt, groundwater).

The model used to define the flow regime types from the hydrological indicators is shown in Figure A.1.
Figure A.1  Conceptual model of flow regime classification.

### A.2 Indicators for the assessment of current status

Spatial scale: Segment/reach  
Type of data: Daily/hourly river discharge series

The hydrological indicators are based on those deriving from the IHA method (D2.1, Part 2 Annex C, Section C.8), integrated with two indicators related to channel-forming discharge ($Q_{p2}$ and $Q_{d10}$), which make use of daily values of stream discharge, and with two specific indicators of hydropoeaking (HP1 and HP2) estimated at the hourly (or sub-hourly) scale (Table A.2). These latter indicators have been introduced to take into account the **hydropoeaking** phenomenon in terms of sub-daily flow fluctuations (HP1) and flow-ramping rate (HP2) (Carolli et al., 2015).

HP1 is defined as the median of the daily values of the difference between the maximum ($Q_{max,i}$) and the minimum ($Q_{min,i}$) daily discharge, divided by the mean daily discharge ($Q_{mean,i}$):

$$ HP_{1,i} = \frac{(Q_{max,i} - Q_{min,i})}{Q_{mean,i}} \quad i \in [0,365] $$

HP1 = median ($HP_{1,i}$)

HP2 is the median of $HP_{2,i}$, which is the 90% percentile of the change in discharge between two successive discharge observations, divided by the observation time interval.

$$ (HP_{2,i})_k = \left( \frac{\Delta Q_k}{\Delta t_k} \right)_{i} = \left( \frac{Q_k - Q_{k-1}}{t_k - t_{k-1}} \right)_{i} \quad i \in [0,365]; k \leq 1 \text{ hour} $$

$$ HP_{2,i} = p_{90} \left( (HP_{2,i})_k \right) $$

HP2 = median ($HP_{2,i}$)
Table A.2  List of Indicators of hydrological alteration.

<table>
<thead>
<tr>
<th>Indicators of Hydrological alteration (Richter et al., 1996)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
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<tr>
<td>12</td>
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<td>32</td>
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<td>33</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Indicators of Hyropeaking (Carolli et al., 2015)</th>
</tr>
</thead>
<tbody>
<tr>
<td>34 - HP1 – Sub-daily flow fluctuations</td>
</tr>
<tr>
<td>35 - HP2 – Flow ramping rate</td>
</tr>
</tbody>
</table>

A.3 Assessment of Hydrological alteration

The Range of Variability Approach (RVA) described in Richter et al. (1997) defines alteration for each IHA indicator, so that it can be used as a guide for managing the relevant flow properties. The RVA uses pre-impact data to express the natural range of flow variation. This natural variation is defined dividing the full range of pre-impact data for each IHA (Table A2) into 3 sectors, delineated by the upper and lower quartiles. An expected frequency with which values of the IHA parameters should fall within each of these three sectors is calculated using pre-impact data and is compared with the observed frequency calculated on post-impact data in order to assess the hydrological alteration.

Two widely-used European methods of hydrological assessment use this approach. The IAHRIS (Martínez Santa-María & Fernandez Yuste, 2010) groups the indicators into 3 different categories (habitual regime, flood regime, drought regime), whereas the IARI method (ISPRA, 2009) estimates a single, average index to assess the hydrological status.
For the purposes of REFORM, we adopt the following tiered approach, as it informs the management of single hydrologic indicators, but also allows the user to further summarize indicators into (grouped) ad-hoc indices.

In order to evaluate the alteration of indicator $i$ (e.g. $Q_{2p}$: 2 year return period peak discharge is referred as no.25 in Table A.2, so $i=25$ in this case), the median value over the post-impact period (e.g. last five years) is calculated, namely $X_{i,k}$. Then, $X_{i,k}$ is compared with the percentiles $X_{N0.25,i}$ and $X_{N0.75,i}$ during the pre-impact period in terms of the distance of $X_{i,k}$ from the nearest percentile.

Successively, the ratio $p_{i,k}$ between the above mentioned distance and the range $X_{N0.25,i}$ - $X_{N0.75,i}$ is calculated (Figure A2). This ratio ($p_{i,k}$) express the alteration of the chosen indicator. Therefore, if $X_{i,k}$ falls inside the inter-quartile range, the $p_{i,k}$ value is recorded equal to 0, which means that there is no alteration.

![Figure A.2 Calculation procedure.](image-url)

The following equation summarizes the calculation method:

$$p_{i,k} = \begin{cases} 
0 & \text{if } X_{N0.25,i} \leq X_{i,k} \leq X_{N0.75,i} \\
\min \left( \frac{X_{i,k} - X_{N0.25,i}}{X_{N0.75,i} - X_{N0.25,i}}, \frac{X_{N0.75,i} - X_{i,k}}{X_{N0.75,i} - X_{N0.25,i}} \right) & \text{if } X_{i,k} < X_{N0.25,i} \text{ or } X_{i,k} > X_{N0.75,i}
\end{cases}$$

where:
- $i$ is the number of the indicator as in Table A.2;
- $k$ refers to the last year of the post impact period;
- $X_{i,k}$ is the median value of the post-impact period in the altered conditions;
- $X_{N0.25,i}$ is the 25% percentile of indicator $i$ in natural conditions (pre-impact);
- $X_{N0.75,i}$ is the 75% percentile of indicator $i$ in natural conditions (pre-impact).
A.4 Indicators of Groundwater-Surface water interaction

Spatial scale: Segment/reach
Type of data: Daily river discharge series

Interaction between groundwater and surface water (GSI) can be defined as the hydraulic, physical-chemical, and biological continuity between groundwater and surface water bodies. Groundwater bodies feed surface water bodies and sustain their flow during dry periods and droughts (eg. Bunke and Gonser, 1997; Dahm et al, 1998).

The river-aquifer system can be considered as a unitary body: thus, groundwater connected rivers can also be seen as the surface expression of the groundwater body to which the river is connected.

The interaction processes between a river and the connected groundwater body depend on climatic, geomorphological, hydrological and hydrogeological factors:

- Geology (stratigraphy, morphology, tectonics) and structural pattern of the aquifer in connection with the river;
- Climate regime and related recharge processes;
- Dynamics of hyporheic zone, which is the groundwater-surface water interface, usually within the alluvial sediments of the river corridor.

The hydrological behaviour of a river, such as its intermittency and perenniality, depends on GSI. Likewise, GSI controls the hydrological response of groundwater stored in the aquifer to precipitation and changing river flows (recharge cycles).

Interaction processes vary in space and time. The spatial scale terminology adopted in the present discussion refers to the REFORM framework (REFORM Deliverable 2.1). Relevant GSI at the various spatial scales of the multi-scale framework are also described in the REFORM Deliverables 2.1 and D6.2 (Part 1).

At the large (regional to catchment) scale, GSI processes affect both regional aquifers and the main rivers that receive groundwater from these aquifers. Interaction between main river networks and groundwater is dynamic and depends on: the geology of groundwater body, the size and morphology of the catchment, and climate.

At the landscape and segment scales, interaction processes also depend on the geological and structural features of the hydrogeological system with which the river is connected, and also the geometry of the hydrogeological boundaries (Castany, 1982).

At the finest sub-reach to geomorphic unit scales, GSI depends on the morphology of the river channel and its floodplain, as well as on the presence and nature of the alluvial sediments and solid geology and the depth and geometry of the hyporheic zone. At this scale, GSI processes impact strongly on the ecological communities of river system, within the channel, riparian zone and hyporheic zones (Dahm et al, 1998).

At the large scale, karstic aquifers show high permeability values, whereas at the fine scale, they show heterogeneous conditions of circulation; they can present very low interaction with the connected river as well as extreme permeability and high water exchange in areas that are most intensely fractured and karstified.

River-aquifer interaction types and hydrological assessment and monitoring methods are summarised in Table A.3 for different spatial units.
Table A.3  Scale dependant GSI and corresponding assessment and monitoring methods.

<table>
<thead>
<tr>
<th>Scale</th>
<th>GW-SW interaction</th>
<th>Hydrological assessment and monitoring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catchment/ Landscape unit</td>
<td>Interaction between main hydrostructures (the basal water circulation) and the large rivers that drain them</td>
<td>Water budget analysis</td>
</tr>
<tr>
<td>Segment/ Reach unit</td>
<td>Interaction between aquifers and rivers</td>
<td>Streamflow measurements to identify gaining and losing stream segments or reaches</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Surveys of groundwater flow directions and intensity and water table levels</td>
</tr>
<tr>
<td></td>
<td></td>
<td>River base flow assessment</td>
</tr>
<tr>
<td>Sub-reach/ Geomorphic unit</td>
<td>GSI interaction in the hyporheic riparian zone</td>
<td>Measurements of water table levels (wells, boreholes, piezometers)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Detailed survey of groundwater flow field</td>
</tr>
</tbody>
</table>

**A.5 GSI monitoring methods**

A wide range of methods are used to measure GSI at different spatial scales. They are summarised in Table A.4 and described in detail in the following sections.

Table A.4  Types of analysis of GSI and related spatial scale.

<table>
<thead>
<tr>
<th>Spatial Scale / GW-SW measures</th>
<th>Water budget analysis</th>
<th>Stream flow measurements</th>
<th>Well network measurements</th>
<th>Dyes and tracers</th>
<th>Chemical and physical profiling (temperature, pH, Electric Conductivity, etc)</th>
<th>Seepage meters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catchment/ Landscape Unit</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Segment/ Reach</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub-reach/ Geomorphic unit</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

1. **Water budget analysis (Catchment scale)**

At catchment scale, GSI processes can be identified by analysis of the water budget. Gauging stations along the river network measure the total volume of water runoff (Total outflow, Figure A.3) and its components (base flow, surface runoff), which can be combined with precipitation measurements to calculate the water going into and out of the catchment and its pathways, including the groundwater component.
Figure A.3 Catchment scale. The water budget in a hydrogeological closed system: 1) Precipitation (rain, snow); 2) Evapotranspiration; 3) Total outflow (total discharge at the outlet gauging section); 4) Net infiltration (aquifer recharge); 5) surface runoff; 6) groundwater flow.

2. Hydrogeological investigations
The dynamics of GSI can be identified through hydrogeological studies that allow aquifer geometry, groundwater preferential flow lines and their interaction with the surface water bodies to be extracted.

The output of these investigations include hydrogeological contour maps which show, for example, lines of equal hydraulic head across the regional water table and the directions of groundwater flow (Figure A.4). These can be developed for typical (average) conditions and also for specific (e.g. wet and dry) conditions, allowing useful comparisons to be made (WMO, 1029, 1994).

Figure A.4 Hydrogeological analysis to identify interaction at catchment scale between river and groundwater flow.
3. Hydrograph analysis (Baseflow - Surface runoff separation)

As seen in the previous Section, hydrogeological studies allow reconstruction of both groundwater flow direction and river-aquifer interaction. Hydrograph analysis allows for the calculation and analysis of variations in the contribution of water volumes from different sources or flow pathways (groundwater and surface water) and thus changes in their contribution to the flow regime over time (Huh et al., 2005). As an example, hydrograph analysis allows dry and wet periods of the hydrological year to be distinguished, for example on a monthly basis, and for these periods to be related to variability in the baseflow index (Figure A.5).

![Figure A.5 A) Hydrograph analysis of the contribution of baseflow to the total discharge during wet and dry periods. B) Increase/decrease of streamflow flow along a river reach monitored using well and discharge measurements (from upstream to downstream).](image)

Wet and dry periods can be highlighted in plots of the mean-monthly hydrograph (e.g. Figure A.5 A). These periods represent, respectively, recharge (wet period) and depletion (dry period) conditions of the river-aquifer system.

4. Streamflow measurements

Streamflow measurements indirectly assess the degree of river-aquifer interaction at reach and segment scales: ‘gaining-stream’ (or ‘losing-stream’) conditions are shown in Figure A.5 B and Figure A.6. In Figure A.6, streamflow measurements are made at the sites Q1, Q2, Q3 and highlight discharge increases (or decreases) from upstream to downstream. The hydraulic equipotential lines are reconstructed on the basis of both streamflow measurements and piezometric levels monitored at A, B, C in Figure A.6. They indicate groundwater flow from the riparian zone towards the river or vice versa.
6.2 Methods for HyMo Assessment

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Figure A.6  GSI during base flow conditions (gaining stream: groundwater feeds the streamflow) and dry conditions (losing stream: streamflow feeds the groundwater). Streamflow measurements along the river reach (Q₁, Q₂, Q₃, from upstream to downstream) allow the flow direction between river and aquifer and the amount of water exchange between the two water bodies to be calculated.

The hydrological indicator, discharge change per unit-length of river ($\Delta Q/Km$) may be positive or negative depending on the type of water exchange. Its determination requires near-synchronous streamflow measurements to be carried out at least seasonally in three or four sections (from upstream to downstream) along the river reach. Techniques for streamflow measurement are detailed in manuals such as WMO guidelines no. 1044 (WMO, 2010).

A further hydrological indicator of river-aquifer exchange is the annual minimum discharge, which provides an estimate of the minimum baseflow contribution to the river. This indicator is derived from river flow time series recorded at gauging stations (Gustard et al., 1992), but where there are no such data, it is possible to estimate the indicator by making purpose-specific streamflow measurements during drought periods.

5. Well network measurements

Water table measurements allow the geometry of the piezometric surface of the aquifer and its interaction with the river to be estimated. River-aquifer interactions can be monitored by means of hydraulic head measurements within the fluvial corridor, particularly in the riparian zone (Figure A.7).

Figure A.7  Hydraulic head measurement through a well.

These monitoring programs are usually carried out on wells, piezometers and micro-piezometers located in the floodplain near the river.

6. Chemical-physical profiling

At sub-reach to geomorphic unit scale, the focus is on processes that take place in the hyporheic zone (Environment Agency, 2005; 2009), namely the transition zone between surface water in the river and the saturated zone within the substrate. The interaction
can be described using several methods, including seepage meter measurements, point
measurements using dyes and tracers (Harvey et al., 1996; 1993), and thermal or other
chemical-physical (pH, conductivity, TDS) profiles (e.g. Voytek et al., 2013).

The physical-chemical characteristics of groundwater (temperature, conductivity, pH,
etc.) differ from those of surface water, so the values observed within the river water
can be used to distinguish between surface water and groundwater components.

Water temperature profiles taken across river cross sections and along river reaches, can
support identification and mapping of groundwater filtration areas into the river channel
through the hyporheic zone (Constantz, 2003). Similarly, profiles of electrical
conductivity and/or pH values can provide an indication of groundwater seepage areas.

7. Dyes and tracers

The use of natural and artificial tracers allows groundwater flow lines and the timing of
underground circulation to be quantified at the fine-local scale (e.g. Sub-reach or
geomorphic unit). Like the chemical and physical analysis, tracer measurements are
taken as point surveys, and give information about local areas at a particular point in
time.

A.6 Hydrological indicators and GSI monitoring

Quantitative monitoring of river-aquifer interaction is based on a set of key hydrological
parameters (rainfall, discharge, water levels, well and piezometric levels, air
temperatures). Starting from these data, hydrological key indicators of GSI can be
calculated. Table A.5 shows the key indicators that have been used for assessment and
monitoring programs of GSI exchange (from Gustard et al. 1992; WMO n.1029, 1994).

Table A.5 Synthesis of Indicators of Groundwater – surface water interaction (modified
after Gustard et al., 1992 and WMO n.1029, 1994).

<table>
<thead>
<tr>
<th>Monitoring techniques</th>
<th>GSI indicator</th>
<th>Unit</th>
<th>Description</th>
<th>Data required</th>
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<tr>
<td>Streamflow measurements</td>
<td>Streamflow</td>
<td>m³/s</td>
<td>Flow data and arithmetic mean of the flow data series</td>
<td>Daily (or monthly) flows</td>
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<tr>
<td>Hydrograph analysis</td>
<td>Baseflow</td>
<td>m³/s</td>
<td>Groundwater contribution to the total flow</td>
<td>Daily flows</td>
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<tr>
<td>Hydrograph analysis</td>
<td>Baseflow index</td>
<td>%</td>
<td>Baseflow as a proportion of the total discharge of a river</td>
<td>Daily flows</td>
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<tr>
<td>Hydrograph analysis</td>
<td>Coefficient of variation in annual mean flow</td>
<td>%</td>
<td>Standard deviation of annual mean flow divided by mean flow</td>
<td>Long term data flow</td>
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<td>Well networks</td>
<td>Groundwater level</td>
<td>(m)</td>
<td>Variation of hydraulic head within an aquifer</td>
<td>Hydraulic head data, observation wells, bore holes or hand-dug wells</td>
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<tr>
<td>Thermal and physico-chemical profiling</td>
<td>Physico-chemical parameters</td>
<td>°C; µS/cm</td>
<td>Variation in physico-chemical parameters along a river section; thermal and water conductivity variations</td>
<td>Physico-chemical data</td>
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<td>Seepage meters</td>
<td>Water flow across bed interface</td>
<td>m³/s</td>
<td>Direct measure by seepage meters of water flow across the hyporheic zone</td>
<td>Seepage data</td>
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</table>
A.7 References


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ANNEX B Morphological monitoring indicators

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Introduction
This chapter reviews indicators, evaluation tools, and analyses which are suitable for monitoring morphological conditions. Monitoring is the repeated measurement of parameters and/or a periodic evaluation by some assessment tool to verify whether some change (deterioration or enhancement) of morphological conditions is occurring compared to some initial condition. The review stems from the outputs of REFORM Deliverable D2.1 (Gurnell et al., 2014), but provides more detail on monitoring indicators, evaluation procedures and tools. The types of monitoring according to the Water Framework Directive (WFD) are discussed, and evaluation of potential impacts of new interventions (including restoration actions) is also considered.

B.1 Indicators for morphological characterization
The information assembled during the characterisation phase supports a list of morphological indicators of current and past condition of a catchment and its spatial units. These key indicators, which are summarised in Table B.1, provide an overview of current and past morphological functioning of the catchment and its spatial units.
Table B.1 List of indicators of current and past condition according to the relevant spatial scale, the key processes and criteria that they represent and the human pressures that influence them (from Gurnell et al., 2014).

<table>
<thead>
<tr>
<th>Spatial Unit</th>
<th>Key Process</th>
<th>Assessed Criteria</th>
<th>Indicators</th>
<th>Alteration Pressures</th>
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<tbody>
<tr>
<td>Catchment</td>
<td>Water Yield</td>
<td>Catchment area</td>
<td>Drainage area (km²)</td>
<td>Water transfers</td>
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<td>Runoff ratio (coefficient)</td>
<td>Water yield (mm)</td>
<td>De/Afforestation</td>
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<td>Geology</td>
<td>Annual runoff ratio (coefficient)</td>
<td>Agriculture / grazing abandonment</td>
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<td>Land cover</td>
<td>Geology (WFD types)</td>
<td>Major land cover change (e.g. urbanization)</td>
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<td>% siliceous, % calcareous</td>
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<td>% organic, % mixed /other</td>
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<td>Land cover (CORINE level 1)</td>
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<td>% forest and semi-natural areas</td>
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<td>% wetlands</td>
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<td>Landscape Unit</td>
<td>Water Production</td>
<td>Rapid runoff production (low infiltration areas, potential saturated areas)</td>
<td>% area of exposed aquifers</td>
<td>Changes in groundwater exploitation / abstraction</td>
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<td>% area of permeability classes</td>
<td>Changes in land cover / use</td>
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<td>% glaciers and perpetual snow</td>
<td>Changes in ice / snow storage</td>
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<td>% large surface water bodies</td>
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<td>Land cover (CORINE level 2)</td>
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<td>% area of rapid runoff production (paved or compacted area, urban fabric, industrial, commercial, transport units, open spaces with little or no vegetation)</td>
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<td>% area of intermediate runoff production (arable land, perm. crops, pastures, shrub and/or herbaceous vegetation)</td>
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<td>% area of delayed runoff production (forests, wetlands)</td>
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<td>Spatial Unit</td>
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<td><strong>Landscape unit (ctd.)</strong></td>
<td>Sediment production</td>
<td>Fine sediment production</td>
<td>Soil erosion rate (t ha(^{-1}) y(^{-1}))</td>
<td>Changes in land cover / use</td>
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<td></td>
<td>Coarse sediment production</td>
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<td>% area with potential sources of coarse Sediment</td>
<td>Intensification of use of agricultural soils</td>
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<td><strong>Segment</strong></td>
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<td>Water flow</td>
<td>River flow regime(^{*})</td>
<td>Flow regime type(^{1*})</td>
<td>Dams, flow regulation, water transfers, hydropower development</td>
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<td></td>
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<td>Average annual flow (m(^3) s(^{-1}))(^{1*})</td>
<td>Average monthly flow (m(^3) s(^{-1}), seasonal pattern)(^{1*})</td>
<td>Groundwater exploitation</td>
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<td>Baseflow index (BFI)</td>
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<td>Morphologically meaningful discharges ((Q_{p\text{median}}, Q_{p21}, Q_{p10}, m^3 s^{-1}))^{1*})</td>
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<td>Extremes: median, LQ, UQ of 1- and 30-day maximum and minimum flows (m(^3) s(^{-1}) and month of most frequent occurrence)(^{1*})</td>
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<td>Hydropeak frequency (number / year)(^{1*})</td>
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<td>Eroded soil delivered to channel</td>
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<td>Sediment flow</td>
<td>Sediment supplied to the channel</td>
<td>Measured / estimated suspended sediment load ((t y^{-1})^{2*})</td>
<td>Dams, flow regulation</td>
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<td>Sediment transport and storage(^{2*})</td>
<td>Measured / estimated bedload ((t y^{-1})^{2*})</td>
<td>Major changes in land cover / use</td>
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<td>Sediment budget ((+ve / -ve channel sediment storage))^{2*}</td>
<td>Removal of riparian vegetation</td>
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<td>Number of high channel blocking structures</td>
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<td>River</td>
<td>Valley morphology</td>
<td>Average valley gradient (m.m⁻¹)</td>
<td>Effective valley width can be reduced by human activities but these lateral</td>
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<td>Groundwater abstraction</td>
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<td>Channelization, dredging / gravel mining</td>
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<td>Average riparian</td>
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<td>Floodplain occupation</td>
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<td>trees</td>
<td>Wood</td>
<td>% active channel edge bordered by living /</td>
<td>Flow regulation / groundwater abstraction</td>
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<td>Production</td>
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<td>dead trees</td>
<td>Dams, weirs and other blocking structures</td>
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<td>Flood area</td>
<td>% floodplain</td>
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<td>Flow energy</td>
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<td>Bed sediment</td>
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<td>Reach (ctd.)</td>
<td>Channel self- maintenance</td>
<td>Braiding index</td>
<td>Anabrancking index</td>
<td>Flow regulation / groundwater abstraction</td>
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<td>/ reshaping</td>
<td>River type</td>
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<td>Bed incision</td>
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<td>(ctd.)</td>
<td>Presence of channel and floodplain type and features</td>
<td>Geomorphic features / units typical of river type</td>
<td>Embanking, revetments</td>
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<td></td>
<td>Channel dimensions,</td>
<td>Bars, benches, islands (% area of bankfull channel)</td>
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<td>Floodplain land occupation</td>
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<td>type and features</td>
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<td>Vegetation encroachment</td>
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<tr>
<td></td>
<td>(ctd.)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Channel Change</td>
<td>Lateral migration, planform</td>
<td>Eroding banks (% active channel bank length)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>/ Adjustments</td>
<td>Laterally aggrading banks (% active channel bank length)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Retention of in-channel sediment (% area of bankfull channel)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lateral channel migration rate (m y⁻¹)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Changes in (i) sinuosity index, (ii) braiding index, (iii) anabrancking index</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Narrowing / widening</td>
<td>Changes in active channel (i) width, (ii) depth, (iii) width:depth ratio</td>
<td></td>
<td>Dams, flow regulation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Presence of geomorphic features / units indicative of (i) narrowing (ii) widening</td>
<td></td>
<td>Groundwater abstraction</td>
</tr>
<tr>
<td></td>
<td>Bed Incision / aggradation</td>
<td>Presence of geomorphic features / units indicative of (i) bed incision, (ii) aggradation</td>
<td></td>
<td>Channelization</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Changes in bed sediment structure indicating (i) incision, (ii) aggradation</td>
<td></td>
<td>Dredging and gravel extraction (sediment deficit)</td>
</tr>
<tr>
<td></td>
<td>Vegetation encroachment</td>
<td>Aquatic / riparian encroachment</td>
<td></td>
<td>Accelerated soil erosion (sediment surplus)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Urbanization</td>
</tr>
</tbody>
</table>
### Spatial Unit: Reach (ctd.)

<table>
<thead>
<tr>
<th>Key Process</th>
<th>Assessed Criteria</th>
<th>Indicators</th>
<th>Alteration Pressures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel adjustments (ctd.)</td>
<td>Constraints on channel adjustment</td>
<td>Width of erodible corridor</td>
<td>Alteration Pressures</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Proportion of potentially erodible channel margin</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Proportion of river bed that is artificially reinforced</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Number of high, medium, low blocking or spanning/crossing structures</td>
<td></td>
</tr>
<tr>
<td>Vegetation succession</td>
<td>Aquatic vegetation</td>
<td>Aquatic plant (i) extent, (ii) patchiness, (iii) species / morphotypes</td>
<td>Flow regulation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Presence of aquatic-plant-dependent Geomorphic units / features</td>
<td>Groundwater abstraction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Proportion of riparian corridor under mainly mature trees, shrubs, shorter vegetation and bare (recruitment sites)</td>
<td>Channelization</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(i) Lateral gradient and (ii) patchiness in riparian vegetation cover classes</td>
<td>Riparian corridor occupation / management</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dominant riparian tree species</td>
<td>Accelerated soil erosion and delivery</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Presence / abundance of large wood</td>
<td>Invasive species</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Presence of wood- or riparian tree-dependent Geomorphic units / Features</td>
<td></td>
</tr>
<tr>
<td>Wood delivery</td>
<td>Large wood and organic debris</td>
<td>Abundance of (i) isolated wood pieces, (ii) in-channel wood accumulations, (iii) channel-blocking jams, (iv) wood in the riparian corridor</td>
<td>Vegetation and wood management</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Dams, flow regulation, flood control</td>
</tr>
</tbody>
</table>

---

1. Flow properties are estimated at the segment level to maximise the likelihood of having suitable flow gauging station records, but could also be estimated at the reach level if suitable flow series are available.

2. Sediment transport is estimated at the segment scale to link with discharge measurements. However, the measurements or estimates are equally applicable at the reach scale where good information may be available on bed material particle size, local channel gradient and width to support modelling.
### B.2 Indicators for morphological monitoring

Starting from the large set of indicators for morphological characterization (Table B.1), a sub-set of potential indicators for monitoring morphological conditions is summarised in Table B.2. The first column reports the main hydromorphological components according to the WFD (continuity, morphology, substrate) to make a more direct link with the requirements of the directive.

**Table B.2 Summary of morphological indicators for monitoring hydromorphological conditions.**

<table>
<thead>
<tr>
<th>Components</th>
<th>Key processes</th>
<th>Morphology</th>
<th>Artificiality</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Longitudinal continuity</strong></td>
<td>Water flow</td>
<td>Channel-forming discharge</td>
<td>Alteration of water flow (dams, impoundments, water abstraction, hydropower)</td>
</tr>
<tr>
<td></td>
<td>Sediment flow</td>
<td>Suspended sediment load Bedload</td>
<td>Alteration of sediment flow (dams, check dams, weirs, bridges)</td>
</tr>
<tr>
<td></td>
<td>Wood delivery</td>
<td>Alteration of wood delivery from upstream and wood transport (dams, check dams, bridges)</td>
<td></td>
</tr>
<tr>
<td><strong>Lateral continuity</strong></td>
<td>Flooding</td>
<td>Width and longitudinal continuity of modern floodplain</td>
<td>Bank protections, artificial levees</td>
</tr>
<tr>
<td></td>
<td>Sediment supplied from hillslopes to the channel</td>
<td></td>
<td>Elements of disconnection (roads, landslide protection) on hillslopes adjacent to the channel</td>
</tr>
<tr>
<td></td>
<td>Bank processes</td>
<td>Bank sediment size</td>
<td>Proportion of protected banks</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Eroding banks</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Laterally aggrading banks</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Width and longitudinal continuity of an erodible corridor</td>
<td></td>
</tr>
<tr>
<td><strong>Pattern</strong></td>
<td>Self-maintenance / channel adjustments</td>
<td>Sinuosity index, Braiding index, Anabranching index, River type</td>
<td>Artificial changes of river course (meander cutting, channelization, etc.), bank protections, dams, check dams, weirs</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Presence, variability and extent of instream geomorphic units</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Presence, variability and extent of geomorphic features in the alluvial</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>plain (including wood)</td>
<td></td>
</tr>
<tr>
<td><strong>Longitudinal profile/Cross-section</strong></td>
<td>Self-maintenance / channel adjustments</td>
<td>Specific stream power (at current mean bankfull width and morphologically meaningful discharge)</td>
<td>Structures altering longitudinal profile and/or cross section (check dams, bank protections, etc.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bed elevation</td>
<td>Interventions altering longitudinal profile and/or cross section (sediment removal)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bed slope</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bankfull channel width</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bankfull channel depth</td>
<td></td>
</tr>
</tbody>
</table>
Indicators listed in Table B.2 concerning morphological elements and parameters (morphology), and indicators concerning artificial elements (artificiality) are illustrated in the next two sections.

### B2.1 Indicators of morphology

In Table B.3, a summary of the main indicators related to natural morphological processes and forms is reported, providing some general information on the assessment method and the range of application for each indicator.

**Table B.3 Summary of indicators of morphology.**

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Assessment method</th>
<th>Range of application</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Longitudinal continuity</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Channel-forming discharge</td>
<td>Field measurement of maximum annual peak stage at a gauging station</td>
<td>All rivers; more significant for single-thread alluvial rivers</td>
</tr>
<tr>
<td>2. Suspended sediment load</td>
<td>Field measurement</td>
<td>All rivers</td>
</tr>
<tr>
<td>3. Bedload</td>
<td>Field measurement</td>
<td>All rivers</td>
</tr>
<tr>
<td><strong>Lateral continuity</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Width and longitudinal continuity of a modern floodplain</td>
<td>Remote sensing, field survey</td>
<td>Partly confined - unconfined rivers</td>
</tr>
<tr>
<td>5. Bank sediment size</td>
<td>Field measurement</td>
<td>Rivers with alluvial banks</td>
</tr>
<tr>
<td>6. Eroding banks</td>
<td>Remote sensing, field survey</td>
<td>Partly confined - unconfined rivers</td>
</tr>
<tr>
<td><strong>Pattern</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Laterally aggrading banks</td>
<td>Remote sensing, field survey</td>
<td>Partly confined - unconfined rivers</td>
</tr>
<tr>
<td>8. Width and longitudinal continuity of an erodible corridor</td>
<td>Remote sensing</td>
<td>Partly confined - unconfined rivers</td>
</tr>
<tr>
<td>9. Sinuosity index</td>
<td>- Remote sensing - Field measurement</td>
<td>- Single-thread large rivers - Single-thread small rivers</td>
</tr>
<tr>
<td>10. Braiding index</td>
<td>- Remote sensing - Field measurement</td>
<td>- Multi-thread large rivers - Multi-thread small rivers</td>
</tr>
<tr>
<td>11. Anabranching index</td>
<td>- Remote sensing - Field measurement</td>
<td>- Multi-thread large rivers - Multi-thread small rivers</td>
</tr>
<tr>
<td>12. River type</td>
<td>- Remote sensing - Field measurement</td>
<td>- Large rivers - Small rivers</td>
</tr>
<tr>
<td>13. Presence, variability and extent of instream geomorphic units</td>
<td>Remote sensing, field survey</td>
<td>All rivers</td>
</tr>
<tr>
<td>14. Presence, variability and extent of geomorphic features in the alluvial plain</td>
<td>Remote sensing, field survey</td>
<td>Partly confined - unconfined rivers</td>
</tr>
</tbody>
</table>
### Table B.3 (continued).

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Assessment method</th>
<th>Range of application</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Longitudinal profile / cross section</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15. Bed elevation</td>
<td>- Total station/GPS survey</td>
<td>- Wadable rivers</td>
</tr>
<tr>
<td>16. Channel gradient or bed slope</td>
<td>- Bathymetric survey</td>
<td>- Non wadable rivers</td>
</tr>
<tr>
<td>17. Bankfull channel width</td>
<td>- Remote sensing</td>
<td>- Large rivers</td>
</tr>
<tr>
<td>18. Bankfull channel depth</td>
<td>- Total station/GPS survey</td>
<td>- Wadable rivers</td>
</tr>
<tr>
<td>19. Width : depth ratio</td>
<td>- Bathymetric survey</td>
<td>- Non wadable rivers</td>
</tr>
<tr>
<td>20. Specific stream power</td>
<td>See 1, 16, and 18</td>
<td></td>
</tr>
<tr>
<td>21. Variability of cross section</td>
<td>- Field assessment/remote sensing</td>
<td>All rivers</td>
</tr>
<tr>
<td><strong>Bed substrate</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22. Bed sediment size</td>
<td>Field measurement</td>
<td>All rivers except bedrock</td>
</tr>
<tr>
<td>23. Bed armouring</td>
<td></td>
<td>Not applied to bedrock,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>boulder-bed and sand-bed rivers</td>
</tr>
<tr>
<td>24. Clogging</td>
<td></td>
<td>Not applied to bedrock and</td>
</tr>
<tr>
<td></td>
<td></td>
<td>sand-bed rivers</td>
</tr>
</tbody>
</table>

In Table B.3, ‘large rivers’ generally indicate channels of relatively large size, i.e. with a channel width ≥ 30 m, whereas ‘small rivers’ indicate channels with a size ranging from intermediate to small (channel width ≤ 30 m). However, a fixed threshold in stream size should be avoided, but the operator should evaluate whether the resolution of available images is sufficient to carry out a remote sensing analysis or field survey is necessary. A monitoring protocol for each relevant indicator is reported below. The monitoring protocol provides definitions and then summarises various aspects, including the morphological and ecological relevance of the parameter, the monitoring (assessment / measurement) methods, ranges of application, spatial scale at which the monitoring is applied, replication or frequency of measurements, difficulties.

#### Longitudinal continuity

Indicators of longitudinal continuity concern the driving variables of channel morphology, i.e. water and sediment flow. These indicators provide invaluable information on sediment transport, but their periodic measurement is difficult to achieve. However, when available they would be extremely useful and could be used when some specific problem related to water and/or sediment discharge needs to be investigated. Given the complexity of the topic, some general considerations are reported for the next three indicators, but specialist texts should be consulted for more detail.

1. Channel-forming discharge

#### Definition

Different morphologically meaningful discharges are used to define the range of potentially channel-forming discharges ($Q_p^{\text{median}}$, $Q_p^2$, $Q_p^{10}$).

#### Relevance

Alteration of channel-forming discharge may have important direct effects on channel morphology and indirect effects on physical habitats.

#### Monitoring methods

Monitoring channel-forming discharge is based on monitoring and updating the data series of annual peak discharge, which is part of the Annex 2A Hydrological monitoring indicators.

#### Ranges of application

Potentially all rivers.

#### Spatial scale

Segment.

#### Frequency of measurement

Hourly or daily discharge.
2. Suspended sediment load

**Definition**
Suspended sediment that is being transported within a river channel by the flow (often past a particular location within a particular time period).

**Relevance**
Alteration of suspended sediment load may have important effects on the development of particular geomorphic units and therefore on the character and diversity of physical habitats. An increase in suspended sediment load may cause alteration of the bed structure (i.e. clogging), which may have direct effects on biological communities.

**Monitoring methods**
Sediment transport is not monitored as commonly as water discharge, and most European rivers have very limited or no sediment monitoring records. Suspended sediment is more commonly monitored than bedload transport, as it is an aspect of water quality that is typically measured by water companies and national environmental agencies. When a gauging station exists and long-term monitoring data are available, continuation of suspended sediment load measurements should be maintained if at all possible. For more details on suspended load sampling and monitoring see Hicks and Gomez (2003).

**Ranges of application**
Potentially all rivers.

**Spatial scale**
Segment.

**Frequency of measurement**
Hourly or daily measurements.

3. Bed load

**Definition**
Sediment that is being transported on the bed of a river channel by the flow (often past a particular location within a particular time period).

**Relevance**
Compared to suspended sediment load, alteration of bed load may have more significant effects on channel morphology, and therefore on the character and diversity of physical habitats.

**Monitoring methods**
Bedload transport is rarely measured along European rivers, and monitoring stations are usually located only in areas where bedload poses a very significant river management problem. As for suspended load, when a gauging station exists and long-term data are available, bedload monitoring activity should be maintained if at all possible. For more details on suspended load sampling see Hicks and Gomez (2003) and Piégay et al. (2008).

**Ranges of application**
Potentially all rivers.

**Spatial scale**
Segment.

**Frequency of measurement**
Hourly or daily measurements.

**Lateral continuity**

4. Width and longitudinal continuity of a modern floodplain

**Definition**
The modern floodplain represents the portion of the overall floodplain that is readily accessible by floodwater. It is therefore an indicator of the lateral continuity of flows. A river in dynamic equilibrium builds a modern floodplain (i.e., a surface created under
current conditions) that is inundated during discharges just exceeding channel-forming flows (typical return interval of 1÷3 years). The presence and extent of a modern floodplain are quantified in terms of its mean width and longitudinal continuity along the reach.

Relevance
The presence of a modern floodplain that is frequently flooded promotes several important morphological, hydrological and ecological functions (attenuation of flood peak discharges, energy dissipation, fine sediment deposition, groundwater recharge, flood pulse, turnover of riparian habitats, etc.). Channel adjustments (specifically bed incision) or artificial structures (levees) can alter this characteristic form and disconnect the floodplain (which becomes a terrace) from channel processes.

Monitoring methods
Remote sensing–GIS: measurement of width and longitudinal continuity (quantitative); Field survey: identification/checking of modern floodplain (qualitative).

Measurement procedure
1. Identification and delimitation of the modern floodplain by remote sensing/GIS and field survey.
2. After the modern floodplain has been delimited, two parameters are used to quantify the presence and extension of this surface: ‘Width’ and ‘Longitudinal continuity’.
3. The “Width of the modern floodplain” \( W_{fp} \) (in m) is intended as the overall width, i.e. the sum along the two sides of the channel including the islands, and is measured by two possible ways: (1) repeated measures along a series of transects to obtain the mean value along the reach (Figure B.1); (2) dividing the floodplain area by the reach length.
4. “Longitudinal continuity of the modern floodplain” \( L_{cfp} \) is expressed as the portion of the reach (in % of reach length) where a modern floodplain exists on at least one side of the river (Figure B.1).

\[
L_{cfp} = \frac{l_1 + l_2 + l_3}{l} \times 100\%
\]

Figure B.1 Measurement of the Width \( W_{fp} \) and Longitudinal continuity \( L_{cfp} \) of the modern floodplain. The green area represents the modern floodplain along the reach. The width is obtained by the average of the cross sectional width measurements along the transects from 1 to 17. The longitudinal continuity is expressed as the percentage of the total reach length \( l \) where a floodplain exists on one or both river sides (i.e. \( l_1, l_2, l_3 \)).

Ranges of application
This indicator is applied to partly confined and unconfined rivers.

Spatial scale
Reach.

Frequency of measurement
Possible changes in the presence and extent of a modern floodplain can be related to lateral mobility of the channel (bank retreat or advance), incision, construction or removal of artificial levees, restoration interventions aimed at floodplain re-creation.
Repeat measurements are only necessary when changes attributable to some of these possible causes occur, otherwise (e.g. in the case of a stable or urbanized river), it is not necessary to replicate the measurement.

### 5. Bank sediment size

**Definition**
This indicator evaluates the typical size of the sediment composing the streambanks.

**Relevance**
The calibre of sediment at the channel boundaries (bed and banks) is another fundamental control on river channel morphodynamics. Bank sediment size influences the erodibility of streambanks, and the size of material that can be delivered to sediment transport by lateral erosion. It also provides information on some characteristics of riparian habitats.

**Monitoring methods**

**Field measurement:** identification of bank sediment size needs a field assessment and preferably field sampling.

**Measurement procedure**
1. The characteristic calibre of bank sediment needs, at a minimum, to be distinguished to the qualitative level of bedrock, boulders, cobbles, gravel, sand and silt, clay. This information is usually collected in the field, although bedrock- or boulder-dominated reaches are sometimes distinguishable on aerial imagery. Some variability of bank typologies (cohesive, non cohesive, composite, etc.) and consequently of the sediment size can be observed at the reach scale, in such case the predominant sizes should be noted. Where there is a mix of two dominant sediment sizes, a combined descriptor can be used such as boulder-cobble.
2. Given that bank sediment size is crucial to characterizing channel morphodynamics, collection of some representative sediment samples from the field is strongly recommended. The following parameters can be extracted if a complete particle size distribution is estimated from such samples: (1) Median particle size / $D_{50}$; (2) Sorting coefficient (width of the particle size distribution); (3) Skewness (asymmetry of the distribution); (4) Kurtosis (peakedness of the distribution).

**Ranges of application**
All rivers except bedrock channels.

**Spatial scale**
The characteristic calibre of bank sediment at a qualitative level is collected at reach scale. Bank sediment sampling is conducted at representative sites.

**Frequency of measurement**
Changes in bank sediment size normally occur at a longer time scale compared to other indicators and so repeat measurements are not usually necessary and a single observation (or periodic measurements with a low frequency) of this indicator can be conveniently used to integrate the characterization of river conditions.

### 6. Eroding banks

**Definition**
This indicator evaluates the length of retreating banks along the reach and the mean rate of bank retreat.

**Relevance**
Bank erosion is often perceived as a negative process. However, eroding streambanks are also a natural feature of channels that are dynamically stable and represent a key process contributing to sediment supply as well as to the development of riparian habitats. Some bank erosion is increasingly recognised to be a positive attribute for aquatic and riparian ecosystems (Florsheim et al., 2008). The rate of lateral changes is also very relevant: high rates of erosion can be related to channel instability, and may be responsible of excessive sediment supply, whereas low rates can be associated to excessive stability.
Monitoring methods

Remote sensing and/or field survey: identification of the presence of eroding banks (qualitative), where eroding banks are normally characterized by natural (unreinforced) unvegetated or scarcely vegetated, vertical, vertical/undercut, and vertical with toe bank profiles.

Remote sensing–GIS: length of eroding banks and rate of retreat (quantitative).

Measurement procedure

1. Identification of eroding banks along the reach by remote sensing and/or field inspections.
2. Two parameters are used to quantify eroding banks: “Length of eroding banks” and “Rate of bank retreat”.
3. The “Length of eroding banks” \( L_{eb} \) (in m and/or % of the sum of the two banks or, equivalently, double the channel reach length) is measured within a GIS as the total length of eroding banks along the reach (Figure B.2).
4. To evaluate the rate of bank retreat, at least two remotely sensed images are compared by GIS analysis spanning a given interval of time. A first step consists of orthorectification and georeferencing of each image, followed by digitising the position of the channel banks.
5. A series of measurements of bank retreat are carried extracted at a regular spatial interval (the same interval used for the measurement of Channel width can be used) within a GIS (Figure B.2).
6. A mean value of bank retreat along the reach is calculated (in the case of stable or advancing banks, bank retreat is assumed equal to zero), and then this is divided by the time in years between the two analyzed images, obtaining a mean “Rate of bank retreat” \( R_{br} \) (in m/year).

\[
L_{eb} = \frac{Leb1+Leb2+Leb3+Leb4}{Lr} \quad (\%) 
\]

Figure B.2 Measurement of the Length of eroding banks \( (L_{eb}) \) (A), and the Rate of bank retreat \( (R_{br}) \) (B).

Ranges of application

This indicator is relevant to unconfined and partly confined rivers. In confined channels lateral erosion is prevented by the presence of hillslopes and is normally insignificant.

Spatial scale
Reach.
6.2 Methods for HyMo Assessment

Part 2. Thematic Annexes

7. Laterally aggrading banks

**Definition**
This indicator evaluates the length of the active channel bank showing stabilising (vegetating) marginal bar, floodplain and bench features, and the rate of bank advance.

**Relevance**
Aggrading banks are common features in a natural channel that is dynamically stable, and are extremely important from an ecological point of view because they are associated to the development of the floodplain and riparian vegetation and habitats.

**Monitoring methods**

- **Remote sensing and/or field survey:** identification of presence of laterally aggrading banks (qualitative)
- **Remote sensing–GIS:** length of laterally aggrading banks and rate of advance (quantitative)

**Measurement procedure**

1. Identification of laterally aggrading banks along the reach by remote sensing and/or field inspections.
2. Two parameters are used to quantify laterally aggrading banks: “Length of laterally aggrading banks” and “Rate of bank advance”.
3. The “Length of laterally aggrading banks” ($L_{lab}$) (in m and/or % of the sum of the two banks or, equivalently, of the double of the channel reach length) is measured within a GIS as the total length of laterally aggrading banks along the reach (similarly to the eroding banks).
4. Similarly to the rate of bank retreat, at least two remotely sensed images are compared by GIS analysis spanning a given interval of time to evaluate the rate of bank advance. A first step consists of orthorectification and georeferencing of each image, followed by digitising the the position of the channel banks.
5. A series of measurements of bank advance along the reach are carried out at a regular spatial interval (the same interval used for the measurement of Channel width can be used) within a GIS.
6. A mean value of bank advance along the reach is calculated (in the case of stable or retreating banks, bank advance is assumed equal to zero), and then this is divided by the difference in years between the two analyzed images, obtaining a mean “Rate of bank advance” ($R_{ba}$) (in m/year).

**Ranges of application**
This indicator is most relevant in the case of alluvial, unconfined and partly confined rivers, but can be also significant in confined channels.

**Spatial scale**
Reach.

**Frequency of measurement**
A periodic assessment of this indicator is related to the availability of new remotely sensed data (aerial photos or satellite images), but an interval of about 6 years is usually feasible.
The presence and a sufficient extent of potentially erodible corridor is a positive attribute, allowing natural lateral mobility and providing a supply of sediment.

**Monitoring methods**

**Remote sensing–GIS**: measurement of width and longitudinal length of the potentially EC (quantitative).

**Measurement procedure**

1. As a first approximation, the EC is first delimited by remote sensing – GIS, as the area not protected by structures (e.g., bank protections, levees) or infrastructure (e.g., houses, roads), since these latter areas would be definitively protected if bank retreat were to occur.
2. After the EC has been delimited, two parameters are used to quantify the presence and extension of this surface: ‘Width’ and ‘Longitudinal continuity’.
3. The “Width of the erodible corridor” \( W_{EC} \) (in m) is intended as the overall width along both sides of the channel, and is measured in two possible ways: (1) repeated measures along a series of transects to obtain the mean value along the reach (similarly to the width of the modern floodplain in Figure B.1); (2) dividing the area of the EC by the reach length.
4. “Longitudinal continuity of the erodible corridor” \( L_{CEC} \) is expressed as the portion of the reach (in % of reach length) where an EC exists on at least one side of the river (similarly to the longitudinal continuity of the modern floodplain in Figure B.1). This measure corresponds to the proportion of channel length with a potentially erodible channel margin on one or both sides.

**Ranges of application**

This indicator is suitable for unconfined or partly confined rivers.

**Spatial scale**

Reach.

**Frequency of measurement**

The extension of an EC can occur in relation to lateral mobility of the channel (bank retreat or advance), construction or removal of structures and infrastructures. Only where some of these possible adjustments occur is a new assessment necessary, otherwise (e.g. in the case of a stable or urbanized river) replicate measurements are unnecessary.

---

**Pattern**

### 9. Sinuosity index

**Definition**

The sinuosity index is the ratio between the distance measured along the (main) channel and the distance measured following the direction of the overall planimetric course of the river. The index generally refers to the bankfull channel. The baseflow sinuosity index can be also of interest, but is more variable, reflecting flow conditions at the moment of the measurement.

**Relevance**

The sinuosity index is an important parameter when classifying the channel pattern of single-thread rivers, since changes in sinuosity index may reflect variations in the overall channel morphology.

**Monitoring methods**

**Remote sensing–GIS**: for rivers of any size (when the planimetric course is visible).

**Field measurement**: for small rivers when excessive riparian vegetation cover prevents the identification of the planimetric course from remote sensing.

**Measurement procedure**

**Remote sensing – GIS**

1. Orthorectification and georeferencing of each image, followed by digitising the
bankfull channel axis or center line, defined as the mid-line between the margins of the bankfull channel.

2. Definition of the ‘axis of the overall planimetric course’ or ‘meander belt axis’. This is the axis of the overall corridor of development of the planimetric pattern or the meanders envelope, as defined by various authors (e.g. Brice, 1964; Malavoi and Bravard, 2010; Alber and Piégay, 2011).

The axis can be a polyline of linear segments, or it can be curvilinear (e.g. Malavoi and Bravard, 2010). In the former case, each linear segment should reflect the changes in direction of the overall course (normally for a length not lower than about 20 times the channel width). Another approach, which is preferable because it minimises subjectivity, defines the meander belt axis as the polyline connecting the inflection points of the channel axis (i.e. the half-meander sinuosity following the terminology of Howard and Hemberger, 1991; see also Alber and Piégay, 2011).

3. Measurement of the channel distance along the channel center and the corresponding distance along the axis of the planimetric course within the upstream and downstream boundaries of the reach.

4. The “Sinuosity index” ($Si$) is calculated as the ratio of the distance along the bankfull channel axis (or center line) to the distance along the axis of the overall planimetric course.

5. Similarly, the “Baseflow sinuosity index” ($Si_{bf}$) can be also measured as the ratio of the distance along the baseflow channel axis (defined at the mid-point between the margins of the water-filled channel at typical baseflow conditions) to the distance along the axis of the overall planimetric course.

**Field survey**
For small streams, the distance along channel the center line is best measured by field topographic survey, while the length distance the axis of the planimetric course can be defined within a GIS, once the channel center line has been visualized.

**Ranges of application**
The sinuosity index is widely used to classify single-thread rivers, particularly those that are unconfined and partly confined. Its measurement is not very informative in the case of confined rivers, where the planimetric pattern is controlled by the hillslopes, and the distance along the axis of the overall planimetric course coincides with the distance along the channel (resulting in theory to a sinuosity index of 1). In the case of braided rivers, the sinuosity index is generally not meaningful for the classification of planform pattern, but it can be useful to assess possible variations of channel morphology through time (e.g., transitions from braided to single-thread). In the case of anabranching rivers, it can be useful to measure the index for each anabranch channel, and the overall sinuosity index can be calculated as the average of the values of from each channel.

**Spatial scale**
Reach.

**Frequency of measurement**
Replication of measurements by remote sensing depends upon the availability of new remotely sensed data (aerial photos or satellite images), but an interval of about 6 years is usually feasible.

**10. Braiding index**

**Definition**
The braiding index is defined as the number of active channels separated by bars at baseflow.

**Relevance**
The braiding index is an important parameter for classifying channel pattern.

**Monitoring methods**
Remote sensing–GIS: for sufficiently large rivers.

Field measurement: for small streams.
### Measurement procedure

**Remote sensing – GIS**

1. **Definition of inter-distance of measurements.** Measurements from at least 10 cross-sections are necessary, spaced no more than one braid plain width apart. For a very accurate measurement, a longitudinal interval of 0.25−1 bankfull widths is recommended (the same inter-distance used for the measurement of other planimetric parameters).

2. For each cross-section, the number of active channels is counted. Only channels that sustain continuous baseflow should be considered. This measurement can be a little subjective, since it is influenced by the flow stage at the time of the image. In order to minimize such errors, images surveyed during extreme situations (such as during or immediately after a high flow event, or during periods of very low flow conditions) should be excluded.

3. The final value of the “Braiding index” \((Bi)\) is the average of the measurements along the reach.

**Field survey**

In the case of small streams, where the resolution of aerial photos is not sufficient to identify baseflow channels, measurements are carried out in the field. In this case, measurements from some representative sub-reaches is usually sufficient.

### Ranges of application

For channel classification, measurement is necessary when more than one active channel is widely observed along the reach. The braiding index is typically used to discriminate braided from transitional (wandering) rivers. It is not meaningful in the case of single-thread rivers, where mid-channel bars are absent or negligible. It could be applicable to high energy anabranching rivers, where more active channels may exist and be separated by bars.

**Spatial scale**

- **Field survey**: representative sub-reach(es) (sites).

**Frequency of measurement**

Replication of measurements by remote sensing is related to the availability of new remotely sensed data (aerial photos or satellite images), but an interval of about 6 years is usually feasible.

### 11. Anabranching index

**Definition**

The anabranching index is defined as the number of active channels at baseflow separated by vegetated islands.

**Relevance**

The anabranching index is an important parameter for classifying channel pattern.

**Monitoring methods**

- **Remote sensing–GIS**: for sufficiently large rivers.
- **Field measurement**: for small streams.

**Measurement procedure**

**Remote sensing – GIS**

1. Definition of inter-distance of measurements. At least 10 cross-sections spaced no more than the maximum width of the outer wetted channel are necessary. For a very accurate measurement, a longitudinal interval of 0.25−1 bankfull widths is recommended (the same interval used for the measurement of channel width).

2. For each cross-section, the number of active channels at baseflow separated by vegetated islands is counted. As for the braiding index, channels that sustain continuous flow should be considered, and images surveyed during extreme situations (flood, drought) should be excluded.

3. The final value of the “Anabranching index” \((Ai)\) is the average of the measurements along the reach.
Field survey
In case of extremely small streams, where the resolution of aerial photos is not sufficient to identify baseflow channels and islands, the measurement is carried out in the field. In this case, measurements from some representative sub-reaches is usually sufficient.

Ranges of application
The anabranching index is typically used to define anabranching rivers. It is not meaningful in the case of rivers where islands are absent or rare. For channel classification, the measurement is necessary when islands are seen reasonably frequently along the reach.

Spatial scale
Field survey: representative sub-reach(es) (site).

Frequency of measurement
Replication of measurements by remote sensing depends upon the availability of new remotely sensed data (aerial photos or satellite images), but an interval of about 6 years is usually feasible.

12. River type

Definition
This indicator defines the morphological type of the river reach. At a first level (“basic river typology”) used for segmentation, the river type is based on valley confinement and morphological planform and therefore on the values of the sinuosity, braiding, and anabranching indices. At a second level (“extended river typology”), other characteristics are taken into account, particularly bed sediment calibre.

Relevance
River type reflects the interactions between driving variables (flow regime and sediment transport) and the boundary conditions characterising a river reach. It is a fundamental feature used for classification and segmentation. Channel types provide a fundamental link between morphological and biological conditions, as they provide information on the characteristic pattern and diversity of physical habitats.

Monitoring methods
Remote sensing–GIS: for sufficiently large rivers.
Field measurement: for small streams. In the “extended classification”, a field visit is necessary for identification of sediment calibre (see indicator 22. Bed sediment size).

Measurement procedure
Basic River Typology (BRT)
1. Measurement by remote sensing-GIS or in the field for small streams of sinuosity, braiding, and anabranching indices, when applicable (see indicators 18, 19, 20).
2. Identification of the river type is based on the range of values of these indices and on valley confinement (Table B.4 and Figure B.3).

Table B.4 Basic River Typology (BRT) based on Confinement and Planform. \( Si \): sinuosity index; \( Bi \): braiding index; \( Ai \): anabranching index.

<table>
<thead>
<tr>
<th>Type</th>
<th>Valley Confinement</th>
<th>Threads</th>
<th>Planform</th>
<th>( Si )</th>
<th>( Bi )</th>
<th>( Ai )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Confined</td>
<td>Single</td>
<td>Straight-Sinus</td>
<td>n/a</td>
<td>approx. 1</td>
<td>approx. 1</td>
</tr>
<tr>
<td>2</td>
<td>Partly confined / Unconfined</td>
<td>Single</td>
<td>Straight</td>
<td>&lt; 1.05</td>
<td>approx. 1</td>
<td>approx. 1</td>
</tr>
<tr>
<td>3</td>
<td>Partly confined / Unconfined</td>
<td>Single</td>
<td>Sinuous</td>
<td>1.05 &lt; ( Si ) &lt; 1.5</td>
<td>approx. 1</td>
<td>approx. 1</td>
</tr>
<tr>
<td>4</td>
<td>Partly confined / Unconfined</td>
<td>Single</td>
<td>Meandering</td>
<td>&gt; 1.5</td>
<td>approx. 1</td>
<td>approx. 1</td>
</tr>
</tbody>
</table>
## D6.2 Methods for HyMo Assessment
### Part 2. Thematic Annexes

<table>
<thead>
<tr>
<th>Type</th>
<th>Valley Confinement</th>
<th>Threads</th>
<th>Planform</th>
<th>Si</th>
<th>Bi</th>
<th>Ai</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Confined / Partly Confined / Unconfined</td>
<td>Transitiona l</td>
<td>Wandering</td>
<td>1 &lt; Bi &lt; 1.5</td>
<td>Ai &lt; 1.5</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Confined / Partly Confined / Unconfined</td>
<td>Multi-thread</td>
<td>Braided</td>
<td>Bi &gt; 1.5</td>
<td>Ai &lt; 1.5</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Confined / Partly Confined / Unconfined</td>
<td>Multi-thread</td>
<td>Anabranching</td>
<td>Bi &lt; 1.5 or Bi &gt; 1.5</td>
<td>Ai &gt; 1.5</td>
<td></td>
</tr>
</tbody>
</table>

**Figure B.3** The seven types of the Basic River Typology (*BRT*).
Figure B.4 Extended River Types 0 to 6.

Figure B.5 Extended River Types 7 to 22.
### “Extended River Typology (ERT)”

At the second level of the “Extended River Typology”, sediment calibre (indicator 22) and geomorphic units (indicator 13) are also considered, obtaining 22 river typologies (Figures B.4 and B.5).

**Ranges of application**

Classification of river type applies to all rivers.

**Spatial scale**

Reach.

**Frequency of measurement**

Temporal changes in channel pattern are monitored by periodically measuring sinuosity, braiding, and anabranching indices and by observation of additional features. Replication of measurements by remote sensing is related to the availability of new remotely sensed data (aerial photos or satellite images), but an interval of about 6 years is usually feasible.

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<table>
<thead>
<tr>
<th>13. Presence, variability and extent of instream geomorphic units</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Definition</strong></td>
</tr>
<tr>
<td><strong>Relevance</strong></td>
</tr>
<tr>
<td><strong>Monitoring methods</strong></td>
</tr>
<tr>
<td><strong>Assessment procedure</strong></td>
</tr>
<tr>
<td><strong>Ranges of application</strong></td>
</tr>
<tr>
<td><strong>Spatial scale</strong></td>
</tr>
<tr>
<td><strong>Frequency of measurement</strong></td>
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<table>
<thead>
<tr>
<th>14. Presence, variability and extent of geomorphic features in the alluvial plain</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Definition</strong></td>
</tr>
<tr>
<td><strong>Relevance</strong></td>
</tr>
</tbody>
</table>
### Monitoring methods

For the classification and survey of geomorphic units, a combination of methods and approaches is used, including: Remote sensing–GIS mapping; Field assessment.

#### Measurement procedure

The Geomorphic Units survey and classification System (GUS) has been specifically developed for this purpose. This methodology is widely illustrated in Deliverable D6.2 Part 4.

#### Ranges of application

All river types found in unconfined or partly confined reaches.

#### Spatial scale

Remote sensing – GIS analysis can be conducted at the reach scale, whereas field survey is normally limited to a representative sub-reach (site).

#### Frequency of measurement

Replication is desirable on representative sub-reaches, particularly following some pressure or intervention.

### Longitudinal profile / Cross section

#### 15. Bed elevation

**Definition**

Bed elevation is usually defined as either the elevation of the deepest point in the channel bed (minimum bed elevation or thalweg) or the mean bed elevation. Bed elevation can be measured at the scale of a single cross-section or at the reach scale as a longitudinal profile. The term “longitudinal profile” refers to a graphical 2D representation of bed morphology, where bed elevation is plotted against longitudinal distance downstream measured along the channel.

**Relevance**

Longitudinal surveys provide the necessary data for estimating a number of other channel properties, including the slope of the thalweg, the spacing of bed morphological units (pools, steps, etc.), and breaks in slope in the channel’s long profile. Temporal changes in bed elevation are used to assess trends in bed-level adjustments.

**Monitoring methods**

*Field measurement:* total station/GPS survey for wadable rivers; bathymetric survey for non-wadable rivers.

**Measurement procedure**

**Bed elevation at a cross-section**

1. Depending upon the level of accuracy desired and the site conditions, various techniques can be used for topographic survey of channel cross-profiles (see also “Channel depth” for more details), but the use of a total station or differential GPS are recommended. Where flows are too deep to obtain measurements of bed elevation by these methods, bathymetric surveys by sonar systems or echo-sounding can be used.

2. For a given cross-section, the “Minimum bed elevation” \((Z_{min})\) (m a.s.l.) is the deepest point of the channel bed. The “Mean bed elevation” \((Z_{mean})\) (m a.s.l.) can be obtained as the average elevation of the points surveyed on the channel bed, starting from the bank toe (banks are generally excluded from this calculation). A weighted average elevation should be used, taking into account the distance between each pair of surveyed points, if the points are not evenly spaced across the section (Figure B.6).
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Z_{\text{mean}} = \frac{\sum_{i=1}^{n} \left( \frac{Z_i + Z_{i+1}}{2} \right) \times X_{i+1} - X_i}{n - 1}

Figure B.6 Calculation of the Mean bed elevation (Z_{\text{mean}}) (by a weighted average of bed elevations in a cross-section).

Longitudinal profile

3. The longitudinal profile is the typical way in which bed elevation is represented at the reach scale. The longitudinal profile of minimum bed elevation can be directly obtained by surveying the deepest points in the bed against the longitudinal distances downstream measured along the thalweg (i.e. the line of minimum bed elevation). A survey of multiple cross-sections is not necessary but, if they are available, the longitudinal profile is obtained by plotting for each cross section the deepest point against the distance downstream.

4. Alternatively, the longitudinal profile of mean bed elevation requires a series of cross-sections to be surveyed along the investigated portion of the river. Cross-sections should be surveyed at sufficiently small intervals to describe changes in bed elevation adequately along the entire investigated reach or a significant portion of it. The longitudinal profile of mean bed elevation is then obtained by plotting the mean bed elevation of each cross-section against the longitudinal distance downstream measured along the channel center line.

Ranges of application

All river types.

Spatial scale

The topographic survey should ideally extend along the entire reach, but if a shorter length is surveyed, survey of a thalweg profile should encompass a sub-reach that is at least 6 - 20 channel-widths in length.

Frequency of measurement

Replication of measurements requires time demanding field topographic surveys, but an interval of about 6 years along selected, representative reaches or sub-reaches is feasible.

16. Channel gradient or bed slope

Definition

“Channel gradient” or “Bed slope” (S) is obtained by dividing the difference between the elevations of two points at the upstream and downstream ends of a reach by the length of the main channel mid-line for single thread and anabranching channels or the midline of the braid plain for multi-thread braided and wandering channels.

Relevance

Of the longitudinal profile parameters, channel gradient is the most widely used in hydraulic models and morphological classifications. Channel gradient is used to calculate flow velocity and discharge at various stages, stream power, shear stress, and other parameters that are relevant to channel processes.

Monitoring methods

Field measurement; DEM.
Measurement procedure
1. Measurement of bed slope is directly obtained from the longitudinal profile of bed elevation (see indicator 15), which requires a topographic survey of the channel bed for the investigated reach or for a representative portion.
2. In the absence of a field survey of bed elevation, DEMs or other digital map data (e.g., derived by LiDAR) can provide sufficient resolution to estimate channel gradient. In such a case, the water surface slope can be estimated at low-flow conditions.
3. In both cases, a more detailed estimation of the range of channel gradients within the reach can be obtained by splitting the channel length into a series of sub-reaches to calculate several slopes and then calculating the average. A systematic analysis based on constant horizontal increments, referred to in the literature as ‘horizontal slice slope’, can be conducted to identify the most appropriate length of the sub-reaches (see for more details Vocal Ferencevic and Ashmore, 2012). In fact, measuring slope over short distances can result in excessive detail that is not related to the scale of the study and may be subject to considerable error, whereas measuring over too large a distance can create a generalized slope that masks elements of real channel form and important local channel-scale slope variation. Because of the sensitivity of estimated slope to the reach length used, a number of different horizontal distances can be tested to identify which might be the most useful for characterising slope at an appropriate level of detail. In any case, an arbitrary decision must be made about the distance over which it is measured.

Ranges of application
All typologies.

Spatial scale
It is necessary to extend the topographic survey of bed elevation for a sufficiently long portion of the reach (ideally it should cover the entire reach), in any case the profile should extend for at least 10 - 20 times the channel width.

Frequency of measurement
Changes in bed slope are an important component of bed-level adjustments that can be tracked by replicating longitudinal profile topographic surveys at regular time intervals.

17. Bankfull channel width

Definition
This indicator is defined as the width of the channel bed, including low flow channel(s) and all instream geomorphic features, in other words the entire width of the channel at the elevation where water would start to spill out onto the floodplain on at least one bank.

Relevance
Channel width is a key parameter to characterize channel morphology and to monitor trends of channel adjustment.

Monitoring methods
Remote sensing–GIS for sufficiently large rivers.
Field measurement: for small rivers.

Measurement procedure
Remote sensing - GIS
1. Orthorectification and georeferencing of each image, followed by digitising of the channel margins and the bankfull axis or center line, defined at the mid-point between the margins of the bankfull channel.
2. Definition of the longitudinal spacing of width measurements (Figure B.7). For an accurate measurement, a longitudinal interval of 0.25÷1 channel width is recommended. This distance can be increased for channels displaying a relatively homogeneous width.
3. Channel width is measured along transects orthogonal to the center-line at each of the previously-defined measurement points. The “Channel width” (W) (m) indicator is
the mean of the width measurements obtained along the reach.

4. An alternative way to calculate the mean channel width at reach scale is to calculate the ratio ‘channel area / channel length’ measured within a GIS. Compared to the previous procedure, a more accurate estimation is obtained, but only one value of mean channel width is obtained with no indication of longitudinal variations in width along the reach.

5. The width of islands is usually excluded from measurements of channel width. However, in such cases, it is useful also to measure the “Total channel width” or “Channel width with islands” (Wt) (in m). For anabranching rivers, the channel width is the sum of the mean widths of the active anabranches, while the total width includes the entire corridor of anabranches and islands.

Figure B.7 Measurement of channel width (W) from remote sensing – GIS. Segments from 1 to 45 represent the transects of measurement at a constant longitudinal spacing and orthogonal to the channel center line. Between sections 17 and 20, measurement of ‘channel width’ (W) will exclude the island (in green), but the island width is included in the ‘total width’ (Wt).

Field survey
In the case of relatively homogeneous channels in terms of width and characteristics, a representative site (or sub-reach) is selected and a minimum of three measurements are made. In the case of a relatively long reach or a reach with subsections of varying width, measurements should be obtained from representative sites. Cross-section surveys (using a differential GPS or total station) provide the best way to measure channel width while also obtaining other cross-section parameters and bed elevation. When measuring width from remotely-sensed sources, the measurements should be orthogonal to the channel center line.

Ranges of application
All typologies.

Spatial scale
Remote sensing – GIS: reach scale.
Field survey: measurements carried out at representative site(s).

Frequency of measurement
Replication of measurements using remote sensing depends on the availability of new remotely sensed data (aerial photos or satellite images), but an interval of about 6 years is usually feasible.

18. Bankfull channel depth

Definition
Channel depth is the difference in elevation between the water surface and the river bed at bankfull conditions.

Relevance
Bankfull channel depth is a useful characteristic of the geometry of a cross-section. Temporal changes in bankfull channel depth indicate the occurrence of adjustments in bed and/or floodplain elevation.

Monitoring methods

Field measurement: total station/GPS survey for wadable rivers; bathymetric survey for non wadable rivers.

Measurement procedure

1. Measurement of channel depth requires a topographic survey of cross-sections and the identification of the bankfull stage, since it is not associated with the water stage during the field measurement. Bankfull stage is identified for each surveyed cross-section as the maximum stage at which water remains contained within the channel without overtopping the banks and flowing onto the floodplain or, for incised channels, onto the lower terrace.

2. Measurement of the cross-sections. A minimum of 3 representative cross-sections should be surveyed perpendicular to the channel axis (center line), and the sections should be located 0.5 to 2 channel widths apart. Techniques employed for cross-section measurements are the same as for bed elevation. A cross-sectional survey should commence on the floodplain (non-incised streams) or higher terrace (incised streams) surface and proceed across the floodplain, down the bank, across the channel, up the opposite bank and finish on the opposite side of the valley. Depending upon the level of accuracy desired and the site conditions, total stations, differential GPS, laser levels, hand levels, or level lines can be used to accomplish the survey. Laser levels with remote sensors allow a single surveyor to collect cross-sectional data, or several surveyors to collect data on various cross-sections concurrently. Hand levels have reduced accuracy and require at least two surveyors. Stretching a level line across a stream channel and directly measuring vertical distance with a graduated staff is commonly used for cross-section measurement, but errors occur when the line is not perfectly level from left to right bank, or when the line sags in the middle.

3. Once cross-sections have been measured, the maximum depth or the mean depth can be calculated. The “Maximum channel depth” \( D_{\text{max}} \) (m) is obtained as the difference between bankfull stage and the minimum bed elevation (thalweg), whereas the “Mean channel depth” \( D_{\text{mean}} \) (m) is obtained as the difference between bankfull stage and mean bed elevation \( Z_{\text{mean}} \), or as the ratio between of cross-section area to width (Figure B.8). The final value of channel depth is the average of the individual cross-section values.

<table>
<thead>
<tr>
<th>Figure B.8 Measurement of Maximum channel depth ( D_{\text{max}} ) and Mean channel depth ( D_{\text{mean}} ) and from the survey of a cross-section.</th>
</tr>
</thead>
</table>

Ranges of application

All river types.

Spatial scale

Measurements are carried out at representative sites.

Frequency of measurement

Replication of measurements requires time demanding field topographic surveys, but an interval of about 6 years at selected sites is feasible.
### 19. Width : depth ratio

**Definition**
This indicator is defined as the ratio of bankfull channel width to mean channel depth.

**Relevance**
The width to depth ratio is used for the characterization of the cross-section geometry. It provides information on the hydraulic conditions and therefore is relevant for physical habitats. Changes of width to depth ratio can reflect variations in channel configuration, as a consequence of changes in width and/or depth.

**Monitoring methods**

*Field measurement*: total station/differential GPS survey for wadable rivers; bathymetric survey for non wadable rivers.

**Measurement procedure**
1. Measurement of channel depth requires a topographic survey of cross-sections. It is recommended to define a minimum of 3 representative cross-sections, spaced from 0.5 to 2 channel widths apart, and surveyed perpendicular to the channel axis (center line) (see “Channel depth” for details).
2. The ratio between bankfull channel width and mean channel depth is calculated for each cross section, and the “Width: depth ratio” (W/D) is the mean value.

**Ranges of application**
All river types.

**Spatial scale**
The parameter is calculated for representative site(s), where channel depth is also measured.

**Frequency of measurement**
Replication of assessment of this parameter is linked to the repetition of the topographic survey of cross-sections for channel depth measurements.

### 20. Specific stream power

**Definition**
Specific stream power is defined as the total stream power divided by the bankfull channel width. Total stream power (Ω) is estimated by combining a morphologically representative discharge (e.g. Q_b (bankfull discharge), Q_p^{median}, Q_p^{2}, Q_p^{10}) and a measure of channel gradient, using the formula:

$$\Omega = \rho g Q S$$

where: Ω is in W m$^{-1}$, ρ is the density of water (1000 kg m$^{-3}$), g is acceleration due to gravity (9.8 m s$^{-2}$), Q is discharge (in m$^3$ s$^{-1}$) and S is bed slope (in m m$^{-1}$). For general application, including at sites where only short flow records are available, Q_p^{median} is recommended as the discharge estimate.

“Specific stream power” (ω) (W m$^{-2}$) is calculated as $\omega = \Omega/W$, where W is the bankfull channel width (m).

**Relevance**
Specific stream power is an indicator of river energy, and is useful for channel / floodplain classification. It is also relevant to biological conditions as it provides information on hydraulic properties and therefore on physical habitat conditions.

**Monitoring methods**

*Data series of annual peak discharge* are required to estimate the morphologically relevant discharge; *Field measurement* (or DEM) to assess channel gradient; *remote sensing – GIS or field measurement* to assess channel width.

**Measurement procedure**
To assess specific stream power we refer to the assessment of channel gradient (see indicator 16) and bankfull channel width (see indicator 17).

**Ranges of application**
All river types.

**Spatial scale**
### 21. Variability of cross section

**Definition**
This indicator evaluates the variability in channel depth along the cross section in relation to what might be expected for the channel type of the investigated reach.

**Relevance**
The natural heterogeneity of forms and surfaces within the channel cross-section, which are representative of the form and complexity of the bed, has several implications in terms of physical habitats and natural functioning of dynamic processes.

**Monitoring methods**
- **Field survey:** visual assessment (qualitative); **remote sensing–GIS:** estimation of length of unaltered portions (quantitative).

**Assessment procedure**
1. A field evaluation is carried out at the scale of some representative sites. In the absence of qualitative or quantitative field observations, the variability in channel depth can be deduced to some extent from the frequency and types of geomorphic units present. In addition, alteration of the natural, expected heterogeneity of forms and surfaces for a given river type caused, for example, by artificial elements or maintenance interventions can also be assessed.
2. Identification by remote sensing of portions of the reach where variability in channel depth exists or, equivalently, where this variability is assessed as altered. The percentage of the reach length with the expected natural “Variability of cross-section” (Vcs) (%) is then evaluated by GIS.
3. For a more detailed assessment of cross section complexity, some quantitative parameter from the survey of a series of cross sections along the reach can be analyzed (e.g., coefficient of variation of depth, cross-section asymmetry, etc.).

**Ranges of application**
All river types. The indicator should be evaluated in relation to the expected natural variability for the given river type. For example, steep, bedrock reaches or low-gradient single-thread reaches may have a natural absence of variability of cross section.

**Spatial scale**
Reach.

**Frequency of measurement**
Replication of the assessment can be periodically carried out by a new field survey and/or when a remotely sensed images are available, particularly in the case that new human impacts exist along the reach.

---

### Bed substrate (including vertical connectivity)

#### 22. Bed sediment size

**Definition**
This indicator evaluates the dominant size of the bed sediment.

**Relevance**
The calibre of bed sediment is a fundamental parameter when characterizing channel type, deriving bed roughness, and estimating critical shear stress for bed motion and bedload. It is also an important property of physical habitats.

**Monitoring methods**
- **Field measurement:** identification of bed sediment size needs a field assessment and, for accurate assessment, bed material sampling.

**Measurement procedure**
1. The characteristic calibre of bed sediment needs, at a minimum, to be distinguished to the qualitative level of bedrock, boulders, cobbles, gravel, sand and silt, clay. This
information is usually collected in the field, although bedrock- or boulder-dominated reaches are sometimes distinguishable on aerial imagery. This information is collected at reach scale: if some variability of bed sediment is observed, the predominant size classes should be noted. Where there is a mix of two dominant sediment sizes, a combined descriptor can be used such as boulder-cobble.

2. Given that bed sediment size is a crucial property for channel morphodynamics, sediment transport, and physical habitat characters, collection of some representative sediment samples from the field is strongly recommended. The following parameters can be extracted if a complete particle size distribution is available: (1) Median particle size / $D_{50}$; (2) Sorting coefficient (width of the particle size distribution); (3) Skewness (asymmetry of the distribution); (4) Kurtosis (peakedness of the distribution). Detailed recommendations concerning bed sediment sampling and analysis can be found in REFORM Deliverable 2.1, Part 2, Annex D.

**Ranges of application**

All rivers except bedrock channels.

**Spatial scale**

The characteristic calibre of bed sediment at a qualitative level is collected at reach scale. Bed sediment sampling for detailed analysis is conducted at representative sites.

**Frequency of measurement**

Changes in bed sediment size normally occur over a relatively longer time scale compared to other indicators. This indicator can be conveniently collected once to integrate the characterization of river conditions, or can be observed periodically at a relatively low frequency to monitor any changes.

### 23. Bed armouring

**Definition**

Bed armouring refers to the presence of a coarser, tightly packed, surface layer of sediment compared to the sub-layer.

**Relevance**

Alteration of bed structure may have significant effects on incipient motion and transport of sediment, on vertical hydrological connectivity, and thus on ecological conditions.

**Monitoring methods**

**Field survey:** visual assessment (qualitative) or comparative sediment sampling of surface layer and sub-layer (quantitative).

**Assessment procedure**

1. A field evaluation is carried out at the scale of one or more representative sites. Presence and extension of armouring is visually assessed.

2. A quantitative assessment of armouring requires sediment sampling and measurements of the surface layer and sub-layer (see Deliverable D2.1, Part 2, Annex D for recommended methods). The “Armour ratio” ($Ar$) can be calculated as the ratio between $D_{50}$ (median diameter of bed sediment) of the surface layer divided by $D_{50}$ of the sub-layer. Two conditions are normally defined: (1) weak (or mobile) armour, when the surface layer is slightly coarser than the sub-layer and is mobilised during floods close to bankfull conditions; (2) static armour, when a marked difference in sediment size exists, and the surface layer is mobilized only during exceptional floods. An armour ratio higher than 3 is often assumed to indicate static armour conditions (Hassan, 2005).

3. Based on visual observations and quantitative assessment, the following three broad cases can be identified: (1) absent: no obvious difference between surface and subsurface bed sediment calibre, i.e. natural heterogeneity of bed sediments in relation to the different sedimentary units (bars, channel bed, pools, riffles, etc.); (2) present: surface bed sediment coarser than subsurface across > 50% of the bed; (3) severe: $D_{50}$ surface >> 3 times $D_{50}$ subsurface across >50% of the bed.

**Ranges of application**
Armouring is only observed on rivers with relatively coarse bed material (gravel, cobble). In the case of a confined stream with coarser bed sediment (boulders), armouring is not considered, as confined channels with a mobile bed have a naturally strong heterogeneity of sediments. It is not evaluated for bedrock or sand-bed rivers, or for deep channels when observation of the bed is not possible.

**Spatial scale**

Representative site(s).

**Frequency of measurement**

Replication of the assessment can be carried out periodically by a new field survey.

### 24. Clogging

**Definition**

Clogging or burial refers to an excess of fine sediments causing interstitial filling of the coarse sediment matrix and potentially smothering of the channel bed (“blanket”: Brierley & Fryirs, 2005, or “embeddedness”: Sennatt et al., 2008).

**Relevance**

Clogging is important because of its effects on the sediment structure of the bed and its physical habitats, which have negative ecological consequences.

**Monitoring methods**

**Field survey**: visual assessment (qualitative).

**Assessment procedure**

1. A field evaluation is conducted at the scale of one or more representative sites. Presence and extension of clogging is visually assessed. Clogging can be normal in particular situations (e.g. in the bottom of pools or along a stream close to hillslopes composed of fine sediment), but it is considered an alteration when it is widespread through a reach.

2. A more quantitative assessment of clogging can be based on an evaluation of the percentage of the bed surface where clogging is visually observed across an investigated site. Pools (where clogging is often observed) are normally excluded. The following broad classes can be used: (1) **absent**: no obvious increase in sand and finer particle content between surface and subsurface bed sediment; (2) **present**: higher sand and finer particle content in surface than sub-surface sediment; (3) **severe**: subsurface intergranular spaces completely clogged with sand and finer particles across > 50% of the bed; (4) **very severe**: sand and finer sediment layer completely burying > 90% of the gravel river bed.

**Ranges of application**

Not evaluated for bedrock or sand-bed rivers, or for deep channels when observation of the bed is not possible.

**Spatial scale**

Representative site(s).

**Frequency of measurement**

Replication of the assessment can be carried out periodically by a new field survey.
B2.2 Indicators of artificiality

Most artificial elements may have multiple effects on different components of morphological conditions (longitudinal or lateral continuity, channel pattern, profile / cross section, substrate). In this section, a list of the main artificial elements is reported, with the information that should be acquired during a monitoring activity, particularly when new artificial elements are added or existing elements are removed. Methods and data sources for monitoring artificial elements include a combination of remote sensing, database (layer) of interventions, field survey, information from public agencies on maintenance practices.

1. Dams

**Definition**

Dams are the hydraulic structures that have the greatest impact on longitudinal continuity of water and sediment.

**Information required for monitoring activity**

1. Location; 2. Year of implementation; 3. Dam height; 4. Dam type; 5. Use (hydropower, reduction of peak flows, water abstraction, etc.); 6. Amount of reduction of peak flows and/or other alterations of flow regime; 7. Sediment management measures, i.e. measures allowing for the flux of bedload downstream.

![Dam](image)

2. Diversion channels and spillways

**Definition**

Diversion channels and spillways are other hydraulic structures that regulate flows.

**Information required for monitoring activity**

1. Location; 2. Year of implementation; 3. Type; 4. Use (reduction of peak flows, water abstraction); 5. Amount of reduction of peak flows and/or other alterations of flow regime; 6. Sediment management measures.

![Diversion channel](image)
3. Retention basins

**Definition**
Retention basins are implemented to reduce flood peaks, and have consequent impacts on the flow hydrograph and in some cases on sediment flow.

**Information required for monitoring activity**
1. Location;
2. Year of implementation;
3. Type (lateral or in-channel);
4. Amount of reduction of peak flows;
5. Measures of sediment management.

![Retention basin](image)

4. Check dams and weirs

**Definition**
Check dams and weirs are transverse structures of a smaller size than dams but that may still have relevant effects on longitudinal continuity. These structures may have different purposes: (1) reduction of sediment discharge to downstream reaches (retention check dams); (2) reduction of bed slope or bed level stabilization (consolidation check dams); (3) water abstraction (weirs).

**Information required for monitoring activity**
1. Location;
2. Year of implementation;
3. Height;
4. Type;
5. Amount of abstracted water (in case of abstraction weirs);
6. Sediment management measures, i.e. measures allowing for the flux of bedload downstream.

![Check dam](image)  ![Weir](image)
## 5. Sills, ramps, and revetments

**Definition and impacts**

Other bed stabilization structures include sills, ramps, and revetments.

**Information required for monitoring activity**

1. Location; 2. year of implementation; 3. type (permeable or impermeable revetments, etc.); 4. length.

<table>
<thead>
<tr>
<th>Sill</th>
<th>Ramp</th>
<th>Revetment</th>
</tr>
</thead>
</table>

## 6. Crossing structures

**Definition**

Crossing structures (such as bridges, fords, and culverts) may interact with water flow, sediment and wood transport.

**Information required for monitoring activity**

1. Location; 2. year of implementation; 3. type of crossing structure and construction material; 4. number of piers (in case of bridges).

<table>
<thead>
<tr>
<th>Bridge</th>
<th>Ford</th>
<th>Culvert</th>
</tr>
</thead>
</table>

## 7. Bank protection

**Definition**

Bank protection consists of longitudinal structures directly protecting the bank from erosion, but also including transverse structures (groynes) that deflect erosive flows and so reduce their direct impact on the banks.

**Information required for monitoring activity**

1. Location; 2. year of implementation; 3. type (walls, rip-rap, revetments, bioengineering, groynes, etc.) and orientation (longitudinal, transverse, oblique); 4. size (height, longitudinal length).
8. Artificial levées

Definition
Artificial levées or embankments are earth or concrete longitudinal structures located at varying distances from the channel banks.

Information required for monitoring activity
(1) Location; (2) year of implementation; (3) type (concrete, earth, reinforced soil, etc.); (4) distance from the banks (set-back, close, bank-edge); (4) size (height, longitudinal length).

9. Artificial changes of river course

Definition
This category includes meander cutoffs, channelization and channel straightening.

Information required for monitoring activity
(1) Location; (2) year of implementation; (3) type; (4) longitudinal extent (length of the artificial reach before and after the intervention).
10. Sediment removal

Definition
Sediment removal may heavily impact channel morphology by modifying the cross-section geometry and bed elevation, reducing available sediment volumes, removing geomorphic units and associated physical habitats, and causing alterations to the bed structure.

Information required for monitoring activity
(1) Location; (2) year of implementation; (3) type (deep pit, bar scalping, bar-edge excavation, etc.); (4) size (length and width of the excavation or of the reach subject to sediment removal); (5) estimation of the volume of sediment removed.

11. Wood removal

Definition
Removal of wood is often carried out in conjunction with sediment removal or vegetation cutting (see indicators of riparian vegetation).

Information required for monitoring activity
(1) Location; (2) year of intervention; (3) length of the reach subject to wood removal; (4) estimate of the volume of removed wood.
B.3 Evaluation of monitoring results

Evaluation of monitoring results can be conducted in various ways. A first option is to analyse monitoring results by visualizing the temporal trend of the selected monitoring indicator. The temporal trend is compared to the past trajectory of a given parameter to understand whether changes are still occurring following such trajectory, or a new trend is observed. A second approach is to use monitored data to periodically apply a method for assessing morphological conditions that summarises the monitoring results by a synthetic index. These two approaches are described in the next two sections.

B3.1 Monitoring and analysis of temporal trends of morphological indicators

This approach employs periodic measurements of some selected morphological parameters or indicators in order to visualise and analyse their temporal trends. This approach is particularly suitable for a detailed investigation that aims to quantify changes and identify their causes.

Selection of the monitored parameters is case-specific and depends upon various factors including: (1) the objectives of the monitoring; (2) the morphological characteristics of the investigated reach; (3) the type of pressure for which a response is being investigated, since the parameters that are most sensitive to the investigated pressure need to be selected.

In general, any indicator described in the previous section could be monitored. However, the following parameters are normally the most relevant:

- Pattern (sinuosity, braiding, or anabranching indices, depending on channel type): these support monitoring of possible adjustments in channel planform and river type in response to some pressure or intervention. Their changes can be measured by remote sensing if a new image is available, or by field survey (particularly for small channels).

- Longitudinal profile / cross section (bed elevation, channel gradient, bankfull channel width, bankfull channel depth, width:depth ratio): these support monitoring of adjustments in bed elevation and channel width in response to some pressure or intervention. Monitoring depends on conducting a new field survey (except channel width that can be measured by remote sensing).

- Bed substrate (armouring, clogging): these can be important indicators of the influence of high impact transverse structures such as dams, retention check dams, and hydropower plants. Visual assessment can be used to establish the existence and longitudinal extent of the alteration but in particularly problematic cases, a quantitative evaluation of the degree of armouring could be required.

The required temporal frequency of the measurements also varies depending on the type of monitoring and on the characteristics of the pressures.

The output of this type of monitoring is the reconstruction of the temporal trend of a selected set of parameters. The evolutionary trajectory of those parameters allows the duration and intensity of the morphological changes to be established and the possible factors influencing such evolution to be understood (i.e., through the construction of potential cause-effect relationships).

For a given morphological parameter (e.g., bed elevation, bankfull channel width, etc.), two types of representation can be constructed: (1) a spatio-temporal distribution, created by plotting the parameter against distance downstream (at reach scale) for different years; and (2) a temporal trend, by plotting the parameter “at-a-station” (i.e., at a specific cross-section) or the reach-averaged value of the parameter against time.

The first type of representation allows visualisation of the spatial variation of a given parameter and, at the same time, comparison of values at the same spatial position in different years (Figure B.9A). The second type of representation provides information on the temporal trend or trajectory of the parameter (Figure B.9B).
B3.2 Periodic evaluation by assessment tools

A second option for analysing monitoring data is to periodically repeat the application of an assessment method that provides a synthetic index of morphological conditions. Repeat values of the synthetic index may reveal changed values induced by an intervention or restoration measure, or occurring independently of any interventions. Among the various available morphological assessment methods, the Morphological Quality Index (MQIm), has been developed for this purpose. The MQIm is a tool for monitoring morphological conditions in the short term, i.e. to evaluate any temporal tendency in morphological conditions (enhancement or deterioration).

A detailed description of the MQIm and the ways in which it differs from the MQI are reported in Deliverable D6.2 Part 3. The MQIm and the MQI are complementary rather than alternative indices. The MQI provides an overall evaluation of morphological conditions and is suitable for classifying and monitoring morphological state (for example, achievement of a good morphological state can be assessed using this index), whereas the MQIm provides an assessment of any short-term trend in morphological quality.

Figure B.9 Two possible ways to represent and visualise temporal changes of a morphological parameter. A) Spatio-temporal distribution; B) Temporal trend.
References


ANNEX C Indicators of riparian vegetation

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Introduction

Riparian vegetation is a key component of river systems, affecting and responding to fluvial processes (Corenblit et al., 2007; Gurnell, 2013; Gurnell et al., 2015), and significantly contributing to trajectories of river changes and recovery from human interventions (González del Tánago et al., 2015). At each spatial scale, different key processes and controls affecting riparian vegetation features can be recognized, resulting in different vegetation units (see Table C.1) that can be used to assess riparian conditions and human pressures (see Table C.2).

The Water Framework Directive includes “structure of the riparian zone” as a hydro-morphological quality element for the classification of ecological status or rivers, taking part of the morphological conditions of water bodies. Thus, the development of practical tools to characterize and monitor the riparian vegetation is needed (González del Tánago & García de Jalón, 2006; Rinaldi et al., 2013), and this task has been fully addressed by the REFORM Project within the Work-packages 2 and 6.

In this document, some indicators to assess the aforementioned vegetation units and features at different spatial scales are developed (Table C.3), whose relevance and monitoring procedure are briefly addressed. The applicability of the proposed indicators are similar in all the cases, as they concern to the cases where the riparian corridor exists, which more likely occurs along partly confined and unconfined valleys. In confined valleys the riparian corridor hardly exists, and the riparian vegetation is naturally restricted or very scarce. Most of the proposed indicators may be assessed by visual appraisal on aerial photographs. Some of them may also be quantified automatically (vegetation patches as landscape metrics, McGarigal and Marks, 1994; Fernandes et al., 2011) whereas others require field work (e.g. species composition, age diversity, recruitment).

In general, vegetation changes gradually following natural growth and succession stages (see Fig. C.1) although they may occur abruptly as a consequence of fluvial disturbances (e.g. flood events, Corenblit et al., 2007) or human interventions. Two times for monitoring the reported vegetation indicators have been proposed, which have been related to the revision of the River Basin Management Plans (RBMP) within the WFD. Once the riparian vegetation has been properly characterized, some indicators are proposed to be monitored each time the RBMP is revised (i.e., each 6 years), whereas others have been proposed to be monitored more frequently (i.e., each 3 years) as they can more closely reflect the influence of fluvial disturbances (e.g. flood events) or human interventions, including restoration measures.
**Table C.1 Multi-scale key processes and controls affecting species composition and structure of riparian corridors.**

<table>
<thead>
<tr>
<th>SPATIAL UNIT</th>
<th>KEY PROCESS FOR VEGETATION</th>
<th>VEGETATION CONTROLS</th>
<th>VEGETATION UNITS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>REGION:</strong></td>
<td>Broad Hydro-geomorphic processes</td>
<td>Bioclimatic Zones Biogeographical Regions (Geology, Relief, Potential Flora)</td>
<td><em>Vegetation Zones</em></td>
</tr>
<tr>
<td><strong>CATCHMENT</strong></td>
<td>Precipitation</td>
<td>Geology Water availability potential Evaporative potentials</td>
<td><em>Riparian Plant Formations</em></td>
</tr>
<tr>
<td></td>
<td>Temperature regime Evapotranspiration</td>
<td>Hydrologic regime Soil texture Land Use Valley dimensions</td>
<td><em>Riparian Plant Associations</em></td>
</tr>
<tr>
<td><strong>LANDSCAPE UNIT</strong></td>
<td>Hillslope Runoff Aquifer storage Sediment supply</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>RIVER SEGMENT</strong></td>
<td>Flow regime Floodplain Infiltration Water table fluctuation Sediment stability Floodplain degradation/aggradation Large wood supply</td>
<td>Flood frequency, magnitude and timing Base flow Channel entrenchment Soil water availability Substratum permeability Alluvial depth</td>
<td><em>Riparian Plant Communities</em></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td><em>Vegetation functional zones</em></td>
</tr>
<tr>
<td><strong>RIVER REACH</strong></td>
<td>Flood disturbance Soil moisture retention Local erosion /deposition processes</td>
<td>Inundation frequency Shear stress Sediment size Sediment cover</td>
<td><em>Vegetation Mosaics, Patches</em></td>
</tr>
<tr>
<td></td>
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<td></td>
<td><em>Vegetation assemblages, guilds</em></td>
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<td></td>
<td></td>
<td><em>Vegetation functional zones</em></td>
</tr>
<tr>
<td><strong>RIPARIAN AND FLOODPLAIN GEOMORPHIC UNITS</strong></td>
<td>Water flowing Sediment stability Shadowing</td>
<td>Water velocity Water depth Light Water Temperature</td>
<td><em>Vegetation Mosaics, Patches</em></td>
</tr>
<tr>
<td><strong>CHANNEL GEOMORPHIC UNIT</strong></td>
<td></td>
<td></td>
<td><em>Aquatic Vegetation Communities, Populations</em></td>
</tr>
</tbody>
</table>


Table C.2  Multi-scale examples of vegetation indicators of functionality and artificiality reflecting potential effects of pressures and impacts in riparian corridors.

<table>
<thead>
<tr>
<th>SPATIAL UNIT</th>
<th>VEGETATION INDICATOR</th>
<th>PRESSURES / IMPACTS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>REGION:</strong></td>
<td><strong>FUNCTIONALITY</strong></td>
<td><strong>ARTIFICIALITY</strong></td>
</tr>
<tr>
<td></td>
<td>Forest/Shrub Vegetation Type</td>
<td>Anthropogenic vegetation types</td>
</tr>
<tr>
<td></td>
<td>Dominant species</td>
<td></td>
</tr>
<tr>
<td><strong>CATCHMENT</strong></td>
<td>Riparian forest Types</td>
<td>Anthropogenic Riparian forests</td>
</tr>
<tr>
<td></td>
<td>Dominant species</td>
<td></td>
</tr>
<tr>
<td><strong>LANDSCAPE UNIT</strong></td>
<td>Riparian / Floodplain vegetation Associations</td>
<td>Changes in species composition/abundance</td>
</tr>
<tr>
<td></td>
<td>Dominant species</td>
<td>% Alien species</td>
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<tr>
<td></td>
<td>Diversity</td>
<td>Valley floor occupation</td>
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<tr>
<td><strong>RIVER SEGMENT</strong></td>
<td>Corridor features:</td>
<td>Corridor narrowing/widening</td>
</tr>
<tr>
<td></td>
<td>Dimensions (average width)</td>
<td>Changes in coverage</td>
</tr>
<tr>
<td></td>
<td>Height and Coverage</td>
<td>Fragmentation</td>
</tr>
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<td></td>
<td>Longitudinal connectivity</td>
<td>Transversal homogeneity</td>
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<tr>
<td></td>
<td>Transversal zonation (lateral/functional zones)</td>
<td>(no different lateral/functional zones)</td>
</tr>
<tr>
<td></td>
<td>Average width</td>
<td>% non-native species</td>
</tr>
<tr>
<td></td>
<td>Species composition</td>
<td>Vegetation encroachment</td>
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<tr>
<td></td>
<td>Vegetation coverage</td>
<td></td>
</tr>
<tr>
<td><strong>RIVER REACH RIPARIAN AND FLOODPLAIN GEOMORPHIC UNITS</strong></td>
<td>Location (distance and elevation from base flow level)</td>
<td>Changes in location due to human intervention</td>
</tr>
<tr>
<td></td>
<td>Species composition and Age-class structure: Recruitment and early stages (&lt; 5y))</td>
<td>Absence of early stages of pioneer species</td>
</tr>
<tr>
<td></td>
<td>Juveniles (5-10 y)</td>
<td>Dominance of late seral-species</td>
</tr>
<tr>
<td></td>
<td>Mature forest (10-50 y)</td>
<td>% Dead trees</td>
</tr>
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<td></td>
<td>Old forest (&gt; 50y)</td>
<td>Dominance of xerophytes herbaceous communities</td>
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<tr>
<td><strong>CHANNEL GEOMORPHIC UNIT</strong></td>
<td>Coverage</td>
<td>Changes in coverage</td>
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<tr>
<td></td>
<td>Species composition</td>
<td>Changes in diversity</td>
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</tbody>
</table>

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Figure C.1  Schematic representation of spatial scales and time to full develop riparian vegetation units and features.

Table C.3 Multi-scale riparian vegetation indicators proposed for characterization and monitoring purposes.

<table>
<thead>
<tr>
<th>Spatial unit</th>
<th>Assessed criteria</th>
<th>Vegetation indicator</th>
<th>Metrics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catchment Landscape unit</td>
<td>Vegetation type</td>
<td>Forest type</td>
<td>Categorical</td>
</tr>
<tr>
<td></td>
<td>Plant formations</td>
<td>Plant formations</td>
<td>Categorical</td>
</tr>
<tr>
<td></td>
<td>Plant associations</td>
<td>Plant associations</td>
<td>Categorical</td>
</tr>
<tr>
<td>River segment</td>
<td>Riparian corridor features</td>
<td>Average riparian</td>
<td>m</td>
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<tr>
<td></td>
<td>corridor width</td>
<td>corridor width</td>
<td></td>
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<tr>
<td></td>
<td>Longitudinal continuity</td>
<td>Longitudinal</td>
<td>% of channel bank</td>
</tr>
<tr>
<td></td>
<td>Coverage</td>
<td>Coverage</td>
<td>% land cover</td>
</tr>
<tr>
<td></td>
<td>Species composition</td>
<td>Species composition</td>
<td>Categorical</td>
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<tr>
<td></td>
<td>Fragmentation</td>
<td>Fragmentation</td>
<td>% of channel bank</td>
</tr>
<tr>
<td></td>
<td>Invasive species</td>
<td>Invasive species</td>
<td>Number</td>
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<tr>
<td></td>
<td>Land use /occupation</td>
<td>Land use /occupation</td>
<td>% area</td>
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<tr>
<td>Patch features</td>
<td>Number of patches</td>
<td>Number</td>
<td></td>
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<tr>
<td></td>
<td>Average size</td>
<td>Average size</td>
<td>m²</td>
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<td></td>
<td>Shape</td>
<td>Shape</td>
<td>Area (m²)/perimeter (m)</td>
</tr>
<tr>
<td>River reach</td>
<td>Age diversity</td>
<td>Age classes</td>
<td>Abundance of classes</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>- Pioneers (1-2 y)</td>
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<td></td>
<td></td>
<td></td>
<td>- Early stages (&lt; 5y)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>- Juveniles (5-10 y)</td>
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<td></td>
<td>- Mature forest (10-50 y)</td>
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<td></td>
<td>- Old forest (&gt; 50y)</td>
</tr>
<tr>
<td>Hydromorphological</td>
<td>Functional zones</td>
<td>Functional zones</td>
<td>% riparian zone under</td>
</tr>
<tr>
<td>interactions</td>
<td></td>
<td></td>
<td>distinct functional zones:</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>- Fluvial disturbance,</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>erosion</td>
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<td></td>
<td></td>
<td></td>
<td>- Fluvial disturbance</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>deposition</td>
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<td></td>
<td></td>
<td></td>
<td>- Inundation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>- Groundwater</td>
</tr>
</tbody>
</table>
C.1 Catchment/Landscape unit scale

**Vegetation type, plant formation and plant associations**

**Definition**

These characteristics represent a broad scale description of riparian vegetation, indicating general attributes of plant communities. Vegetation Type is indicative of the forest typology based on the dominant species (e.g., coniferous vs. deciduous forest). Plant formations refers to the general morphotype of vegetation communities (e.g. shrub, tree galleries) whereas Plant associations intend to explicit the species composition of dominant species (e.g., riparian mixed galleries with *Betula* sp. and *Fraxinus excelsior*).

**Relevance**

Represent the first step in riparian vegetation characterization and are indicative of biogeographic and climatic (i.e., altitude) conditions. They are essential to compare current status with potential status of vegetation, to understand composition and structure of plant communities at smaller scales and to exchange experiences on riparian vegetation management and restoration across different regions.

**Monitoring methods and measurement procedure**

Literature review and General Data Base from Corine Land Cover, GlobCover Land Cover V2 that is also a global land cover map ([http://due.esrin.esa.int/globcover/](http://due.esrin.esa.int/globcover/)). References of Forest types can be found in EEA (2006), and plant associations can be defined according to the Habitat Directive (main systems of habitat and vegetation classification employed in Europe (EUNIS/CORINE and Natura 2000).

**Ranges of application**

All rivers.

**Spatial scale**

Catchment and Landscape Unit scale, although they can be also used as the first step in characterizing riparian vegetation structure at smaller scales (i.e., river segment, reach).

**Frequency of measurement**

These attributes represent basic information of vegetation and remain quite stable over time. In absence of direct human interventions, their monitoring can be done every six years.

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C.2 River segment scale

**Average riparian corridor width**

**Definition**

The indicator refers to the average dimensions in width of the lateral bands along the channel covered by riparian vegetation, which are clearly differentiated from the adjacent land cover or uses. It could be estimated for each side of the channel (i.e., left and right band) or for the river corridor as a whole. It largely depends on valley type and river size.

**Relevance**

One of the most important features of the lateral dimension of the river corridor, indicating the magnitude of the role of vegetation influencing flow resistance and fluvial processes (sediment erosion, deposition). It is indicative of the integrity of the river corridor (riparian width or current dimensions) vs. floodplain width or potential dimensions) and their associated ecosystem functions (e.g., retention of nutrients, habitat and corridor for birds, wildlife, etc.).

**Monitoring methods**

Remote sensing – GIS: direct width measurements on aerial photographs.

**Measurement procedure**

1. Identification and delimitation of the riparian corridor, considering each margin
along the active channel (Fig. C.2: A and B).

2. Measurements of riparian corridor width along perpendicular transects to the channel, and estimation of average values for the respective river segment.

![Example of delineation of riparian corridor where width measurements may be carried out.](image)

**Figure C.2** Example of delineation of riparian corridor where width measurements may be carried out.

**Ranges of application**
All rivers with distinct riparian corridor (i.e., partly confined or confined segments). In confined valleys the riparian corridor is naturally reduced or does not exist.

**Spatial scale**
River Segments, Reaches. It should be referred to a certain length of the channel.

**Frequency of measurement**
Once every six years or after significant flood events.

**Pressures**
Agriculture, urbanization, infrastructures, flood defence works, etc. often occupy the lateral dimension of the riparian corridor reducing its width. As a general rule, in partly confined or unconfined rivers any value of riparian corridor width smaller than 2 times the channel width, or less than 30-45 m on large rivers, should be considered as artificially reduced.

Average riparian corridor width = (A+B)/(2*length)

\[ \text{e.g. } 734243.5 / (2 \times 2372.3) = 154.8 \text{ m} \]
Longitudinal continuity

Definition
The indicator refers to the proportion of the length of the channel maintaining continuous riparian corridor with relative natural and homogeneous conditions.

Relevance
The longitudinal continuity of the riparian corridor assures the continuity of its hydromorphological and ecological functions along the channel. The opposite attribute of longitudinal continuity is fragmentation.

Monitoring methods
Remote sensing – GIS: direct measurement or appraisal on aerial photographs.

Measurement procedure
1. Delineation of river’s margins distinguishing the length occupied by riparian corridor from the length of the discontinuities.
2. Longitudinal continuity estimation based on the proportion of bank length with riparian vegetation in each channel side (Fig. C.3).

Figure C.3 Schematization of the measurement procedure of riparian corridor continuity.

Ranges of application
All rivers with distinct riparian corridor (i.e., partly confined or confined segments).

Spatial scale
River Segment, River Reach.

Frequency of measurement
In absence of human interventions, once every six years.

Pressures
Floodplain occupation or other human interventions affecting the riparian zones usually result in fragmentation of vegetation forest, decreasing its longitudinal continuity. Fragmentation should be assessed by the number of open spaces along the corridor and by the intensity of these open spaces acting as barriers for the organisms. Thus, fragmentation is always relative to the specific communities or species it is indicative for.
**Coverage**

**Definition**
Coverage of riparian corridor corresponds to the fraction of ground covered by vegetation.

**Relevance**
It quantifies the spatial extent of vegetation and also indicates the percentage of bare soil within the riparian corridor.

**Monitoring methods**
Remote sensing – GIS: direct estimation on aerial photographs.

**Measurement procedure**
1. Direct estimation from observations of ortophotos, distinguishing vegetation coverage from open spaces
2. Indirect estimation, as this variable is highly related with NDVI (*Normalized Difference Vegetation Index*) easily estimated by remote sensing with automated procedures.

**Ranges of application**
All rivers with distinct riparian corridor (i.e., partly confined or confined segments).

**Spatial scale**
River Segment, Reach.

**Frequency of measurement**
Vegetation Coverage could change gradually (i.e., vegetation growth) or sharply because of fluvial disturbances (i.e., floods). In absence of human interventions, it could be monitored every three years, being related with longitudinal continuity.

**Pressures**
Vegetation management, grazing or other human interventions may reduce natural coverage of riparian vegetation. By the contrary, damming and flow regulation may artificially increase riparian vegetation coverage after promoting vegetation encroachment below dams.

---

**Species composition and vegetation structure**

**Definition**
It indicates the range of species that are present in the riparian zones, and their spatial structure. Complementary to this characteristic could be the species richness (number of species) and percentage of native species.

**Relevance**
The species composition assesses the naturalness of the riparian vegetation. The spatial structure of vegetation stands may be associated to functional zones indicative of hydromorphological processes and vegetation interactions. It also defines the importance of exotic or invasive species and abundance of mats, reeds, nitrophilous or ruderal species.

**Monitoring methods and measurement procedure**
Field survey: identification and checking species composition of vegetation stands (qualitative) and identification of vegetation character (i.e., native, exotic, invasive, nitrophilous or ruderal species). Spatial distribution should be assessed by identifying functional zones where fluvial disturbance with erosion and deposition processes are dominant, or where riparian soil moisture is primarily replenished by inundation or groundwater.

**Ranges of application**
It could be assessed in all type of rivers.

**Spatial scale**
River Segment, Reach.

**Frequency of measurement**
Description of Species composition and vegetation structure is essential to characterize the riparian corridor, and should be done every three years, to monitor the
conservation status and potential of species invasion.

**Pressures**

Poplar plantations may exist within the riparian corridor, replacing natural riparian vegetation. Other pressures such as flow regulation or channelization works that reduce the frequency of fluvial disturbance may gradually promote the introduction of non-riparian species as well as the expansion of other exotic or invasive species. Water pollution or soil fillings may also promote the growth of nitrophilous or ruderal species.

**C.3 River reach scale**

<table>
<thead>
<tr>
<th>Number of vegetation patches</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Definition</strong></td>
</tr>
<tr>
<td><strong>Relevance</strong></td>
</tr>
<tr>
<td><strong>Monitoring methods</strong></td>
</tr>
<tr>
<td><strong>Measurement procedure</strong></td>
</tr>
<tr>
<td>2. Once the polygons are digitized, the number of patches are counted either as the total number or number of each class of patches.</td>
</tr>
</tbody>
</table>

| Ranges of application | All rivers with distinct riparian corridor (i.e., partly confined or confined segments). |
| **Spatial scale** | River segment, Reach. |
| **Frequency of measurement** | Number of patches may be reduced by vegetation growth or encroachment, or increased by vegetation fragmentation due to many reasons. For regular monitoring it may be assessed every 6 years, or after significant human intervention or flood event. |

<table>
<thead>
<tr>
<th>Patch size: average and variation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Definition</strong></td>
</tr>
<tr>
<td><strong>Relevance</strong></td>
</tr>
<tr>
<td><strong>Monitoring methods</strong></td>
</tr>
<tr>
<td><strong>Measurement procedure</strong></td>
</tr>
<tr>
<td>2. Once the polygons are digitized, areas could be calculated and also the coefficient of variation based on vegetation type. This task could be easily done by using the ”Patch Analyst” tool (vector Format) for ArcGis.</td>
</tr>
<tr>
<td><strong>Ranges of application</strong></td>
</tr>
</tbody>
</table>
**Spatial scale**
River segment, Reach.

**Frequency of measurement**
For regular monitoring it may be assessed every 6 years, or after significant human intervention or flood event.

---

**Patch shape**

**Definition**
The shape of patches describes relationships between perimeter and area. It is indicative of irregularity or complexity of current shape of vegetation patches by rapport to circular or rectangular shapes having the same perimeter or area. In particular, the indicator of shape is the *Mean Shape Index*: a configuration landscape metric which relates the patch area and its perimeter.

**Relevance**
The shape of vegetation patches is indicative of their edge effect. Convoluted shapes indicate large boundaries, expressing high interactions with the adjacent matrix.

**Monitoring methods**
Remote sensing – GIS.

**Measurement procedure**
1. The first step is the delineation of patches.
2. Once the polygons are digitized, mean shape indexes of each vegetation type could be automatically calculated by using the “Patch Analyst” tool (vector Format) for ArcGis.

**Ranges of application**
All rivers with distinct riparian corridor (i.e., partly confined or confined segments).

---

**Age diversity**

**Definition**
Age diversity refers to the number of age classes exhibited by the existing riparian vegetation. As a minimum, four or five age classes should be differentiated: recruitment or seedlings, young forest, mature forest and old forest. Other categories can be also considered: pioneer (1-2 y), early growth/stages (< 5y), juvenile (5-15 y), mature forest (15-50 y), and old forest (> 50y). For each species, size of plants corresponding to these ages (in terms of total height or stem diameter) should be established.

**Relevance**
Age diversity is indicative of the health of the riparian zone and the degree to which it is being modified and turned over by fluvial disturbances. The coexistence of diverse age classes reflects sustainability of riparian vegetation under current hydrological conditions, and the recruitment of pioneer species is indicative of maintenance of mechanisms of natural regeneration.

**Monitoring methods and measurement procedure**
Field survey is necessary to record age classes of plant species. Age categories can be assessed by height or stem diameter measurements.

**Ranges of application**
All rivers with distinct riparian corridor (i.e., partly confined or confined segments).

---

Spatial scale
River segment, Reach.

**Frequency of measurement**
For regular monitoring it may be assessed every 6 years, or after significant human intervention or flood event.
Once every six years or after significant flood event. Recruitment of Salicacea, as the more representative pioneer vegetation of riparian forest in European rivers, could be monitored more frequently, once every 3 years or after significant fluvial disturbances or rehabilitation measures, as it represents a good indicator of human pressures and restoration success.

**Functional zones**

**Definition**
Functional zones refer to the distinct bands or areas covered by riparian vegetation supporting different hydromorphological interactions: (1) Fluvial disturbance dominated areas with predominant erosion processes resulting in coarse substratum; (2) fluvial disturbance dominated areas with predominant deposition processes resulting in finer substratum; (3) inundation dominated areas with low erosion-deposition effect; (4) groundwater or soil moisture regime dominated areas (Gurnell et al., 2015).

**Relevance**
These four functional zones usually exist along the riparian corridors, with different extension according to river typology and biogeographic context. They are indicative of full river functioning and may be used as references for assessing riparian vegetation status and vegetation recovery after restoration measures.

**Monitoring methods and measurement procedure**
Field surveys are necessary to identify predominant fluvial interactions affecting riparian vegetation composition and structure. Delineation on aerial photographs is necessary to assess the percentage of area occupied by each functional zone (Fig. C.4).
Figure C.4  Identification of functional zones along the riparian corridor and changes over time in the Porma River (NW Spain) (see text and Gurnell et al., 2015 for full functional zones explanation).

Ranges of application
All rivers with distinct riparian corridor (i.e., partly confined or confined segments).

Spatial scale
River segment, Reach.

Frequency of measurement
Once every three years or after significant flood event.
References


McGarigal, K., Marks, B.J., 1994. FRAGSTATS: Spatial Pattern Analysis Program for Quantifying Landscape Structure (Vesion 2.0). Forest Science Department, Oregon State University, Corvallis.

**ANNEX D Hydrodesmorphological models**

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Deltas, The Netherlands

**D1. What is a model?**

A model is a representation of aspects of reality for a specific purpose. Hence it is not a replica of reality. Models occur in a wide variety, from simple descriptions (word models) to complex three-dimensional computer models. In a general sense, everybody thus uses models. In a more restricted operational sense, however, the term “models” usually refers to mathematical models that run on computers.

**D2. Which types of models can be distinguished?**

As models occur in a wide variety, it is useful to distinguish different types. The figure below gives an overview.

![Diagram of different types of models]

**Figure D.1  Summary of different types of models.**

Models can be divided into abstract models (models you cannot touch) and physical models (models you can touch). Abstract models can be divided into conceptual models, such as word models and graphical representations, and mathematical models, based on mathematical formulas or equations. Deriving these formulas or equations from data leads to empirical models (induction or data-oriented approach). Deriving them from general principles leads to theoretical models (deduction). The latter are called “physics-
based” if general laws of physics are used for the general principles (process-oriented or mechanistic approach). Some controversial models in hydromorphology use non-physics-based principles such as minimum energy dissipation or maximum sediment transport, but those models are not generally accepted.

The equations of mathematical models can be solved in two ways. One way is that they are simplified to an amenable form for analysis. This leads to analytical models. The other way is that they are translated into a form that can be solved by a computer. This leads to numerical models.

Rules of thumb are simple, easy-to-use quantitative models. They are derived from empirical or analytical models.

Physical models can be divided into scale models and analogue models. Scale models are models constructed at a reduced scale, similar to miniature parks. Scale laws and scale rules translate measurements in the model to values in the real world. Analogue models were used in the past, based on analogies between different physical systems. For instance, currents in an electrical circuit are similar to currents in a river network. Amperes and volts in the electrical circuit thus provided information on discharges and water levels in the corresponding river network.

The true picture is nonetheless more complex. Physics-based hydromorphological models include empirical elements too, such as predictors for hydraulic resistance or sediment transport. Empirical models can also result in complex computer models, for instance if they are based on neural networks. The subdivision presented here serves only as general guidance, without including all the subtleties of advanced or hybrid forms.

D3. What is the use of numerical models in river restoration?

The term “models” usually refers to numerical models, based on mathematical equations and running on computers. They can be used for various purposes in river restoration:

- Integration of knowledge on a river in a structured database
- Assessment of a hydromorphological state, enhancing the information from field measurements (“clever interpolation”)
- Identification of data requirements for monitoring or measurement campaigns
- Evaluation of the effect of pressures
- Evaluation of the effect of restoration measures
- Evaluation of the effect of scenarios such as scenarios of climate change
- Establishment of design conditions for restoration measures
- Analysis of the sensitivity around tipping points such as the transition between meandering and braiding
- Scientific research and testing of hypotheses, for instance about how hydromorphology interacts with the development of vegetation
- Communication, as a tool for explanation and a basis for discussion

The usefulness of numerical modelling in a particular case depends on the needs to meet these purposes, not on data availability. A lack of data is almost never a valid reason to abstain from modelling.

D4. Who can use numerical models?

The use of numerical models requires background knowledge and training. Staff of river management authorities can feasibly meet these requirements for the simpler numerical models, but usually needs to contract out the application of more complex numerical models. A precise distinction is hard to give. One-dimensional (1D) hydrodynamic models are usually routine tools for management authorities, whereas two-dimensional
depth-averaged (2DH) or three-dimensional (3D) morphodynamic models commonly require the involvement of specialized modellers. Most restoration projects do not need 2DH or 3D morphodynamic models. These models are important tools, however, when restoration interferes with navigation.

**D5. What is the use of analytical models in river restoration?**

One might question the use of analytical models based on simplified equations for physical processes if numerical models are available with a more complete representation of physical processes. However, analytical models provide convenient tools for rapid assessment and rules of thumb. This is the main utility of analytical models in river restoration.

It is worth noting, however, that analytical models are also important for the numerical models used in river restoration. Analytical solutions of mathematical equations are complementary to numerical solutions, as they offer additional insights into the fundamental behaviour of the corresponding physical system. Designing numerical models requires analytical models to determine the appropriate numerical scheme and the type and location of the boundary conditions to be imposed. Analytical models also help the optimization of calibration strategies for numerical models, as they reveal which parameters are responsible for different aspects of the solution. They help the interpretation of results from numerical models as well, because numerical solutions may exhibit spurious wiggles, phase lags or attenuation that in this way can be distinguished from real physical phenomena. Finally, analytical solutions provide exact solutions for certain idealized cases that may serve as validation cases for numerical models.

**Table D.1 Comparison of spatial scales for hydromorphological assessment and models.**

<table>
<thead>
<tr>
<th>Hydromorphological assessment</th>
<th>Hydromorphological models</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Name (Wright &amp; Crosato, 2011)</td>
</tr>
<tr>
<td>catchment</td>
<td>river basin</td>
</tr>
<tr>
<td>landscape unit</td>
<td>10^2 – 10^4 km^2</td>
</tr>
<tr>
<td>segment</td>
<td>10 – 100 km</td>
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<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>reach</td>
<td>0.1 – 10 km (&lt;20 widths)</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>geomorphic unit</td>
<td>1 – 100 m (0.1 – 20 widths)</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>hydraulic unit</td>
<td>0.1 – 10 m</td>
</tr>
<tr>
<td>river element</td>
<td>0.01 – 0.1 m</td>
</tr>
</tbody>
</table>

**D6. How to deal with different scales?**

That models deal with aspects of reality rather than full reality is closely related to scale. On the scale of meander bends and floodplains, models do not represent the details of ripples on the river bed. Ripples are then merely noise represented by averaged quantities such as average bed level and hydraulic resistance (parameterization). On the scale of detailed flow patterns and sediment transport around ripples and dunes on the
river bed, the overall picture of the river basin is less important. Influences from far away are captured in the boundary conditions for a local area.

The scale under consideration determines the level of detail and the appropriate modelling approach. For hydromorphological models, scales are defined in another way than for hydromorphological assessment. They are based on relative space scales of morphological features for hydromorphological models, but on partly absolute space scales of areas considered for hydromorphological assessment. As a result, the space scale quoted for the same area and morphological features is smaller for hydromorphological models than for hydromorphological assessment. The table below shows a comparison. Note that the term “reach” refers to different scales in the two systems.

The depth and process scales are realms of scientific research on elementary processes and their interactions. The corridor and cross-section scales are appropriate for analysis of ecosystem degradation, design of river restoration projects, assessment of habitat diversity, and assessment of the sustainability of restoration. The river basin and reach scales are appropriate for analysis of ecosystem degradation and assessment of the sustainability of restoration too, and also for large-scale and long-term impact assessment of restoration.

**D7. Which models are presented in the REFORM wiki?**

The REFORM wiki contains factsheets of the following hydromorphological models:

- 0D analytical models for flow in compound cross-sections
- 0D analytical models for morphology on long time scales
- 0D sediment budget and routing models
- 1D analytical models for gradually-varied flow
- 1D analytical models for morphology on short time scales
- 1D numerical hydrodynamic models
- 1D numerical morphodynamic models
- 2DH numerical hydrodynamic models
- 2DH numerical morphodynamic models
- 3D numerical hydrodynamic models
- 3D numerical morphodynamic models
- Analytical models for bar patterns and braiding threshold
- Bank dynamics models
- Hydrogeological groundwater-surface water models
- Hydrological rainfall-runoff models
- Numerical meander models
- Soil erosion and sediment yield models

**References**